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STORMS CAUSING HARBOR AND SHORELINE  
DAMAGE THROUGH WIND AND WAVES  
NEAR MONTEREY, CALIFORNIA

HARRY L. BIXBY

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STORMS CAUSING HARBOR AND SHORELINE  
DAMAGE THROUGH WIND AND WAVES  
NEAR MONTEREY, CALIFORNIA

by

Harry L. Bixby, Jr.

Lieutenant Commander, United States Navy

Submitted in partial fulfillment of  
the requirements for the degree of

MASTER OF SCIENCE  
IN  
METEOROLOGY

United States Naval Postgraduate School  
Monterey, California

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LCDR Bixby was given 5 years (after completing his course work in 1962) to complete his Thesis. He was awarded his degree in 1965 when he returned as an instructor



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## ABSTRACT

Wind and wave action, accompanying severe rainy-season storms, occasionally has caused considerable damage to the shoreline, harbor installations, and small craft at Monterey, California. In order to gain information about these storms that might lead to forecasting techniques, a complete list of such storms for the 50-year period from 1910 to 1960 was made through a search of local newspaper files. The most significant storms, their frequency of occurrence, the synoptic situations with which they were associated, and the hindcasted sea condition that accompanied them are described.

Two general types of damaging storms were found to exist: one occurring offshore in the open ocean and causing shoreline erosion and flooding by the action of sea and swell; the other, a local windstorm sweeping across Monterey Bay and causing damage to vessels in the harbor mainly by the combined effects of strong gusty winds and short-period seas generated in the bay. Wave hindcasts were made to facilitate comparisons of storm intensities within each of the two types of storms. These comparisons, in terms of the intensity of wave conditions, were made using a quantity called Damage Potential, a function of the size and duration of the storm waves. Synoptic situations with which these storms were associated were classified by a weather-typing system. All storms were found to be associated with one of three principal types. The possibility of an objective-type forecasting technique for the windstorms is discussed.

The author is indebted to Professor Warren C. Thompson and Professor Robert J. Renard, Department of Meteorology and Oceanography, for their patience, encouragement, and invaluable assistance in the course of this study.

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## 1. Introduction.

Throughout the passage of years, storms have occurred in the vicinity of Monterey, California which have caused erosion of the coastline, damaged or destroyed piers and other waterfront structures, and wrecked small craft, particularly those of the fishing fleet. The purpose of this research was to study recent storms and storm-wave occurrences and to relate them to the weather conditions that produced them.

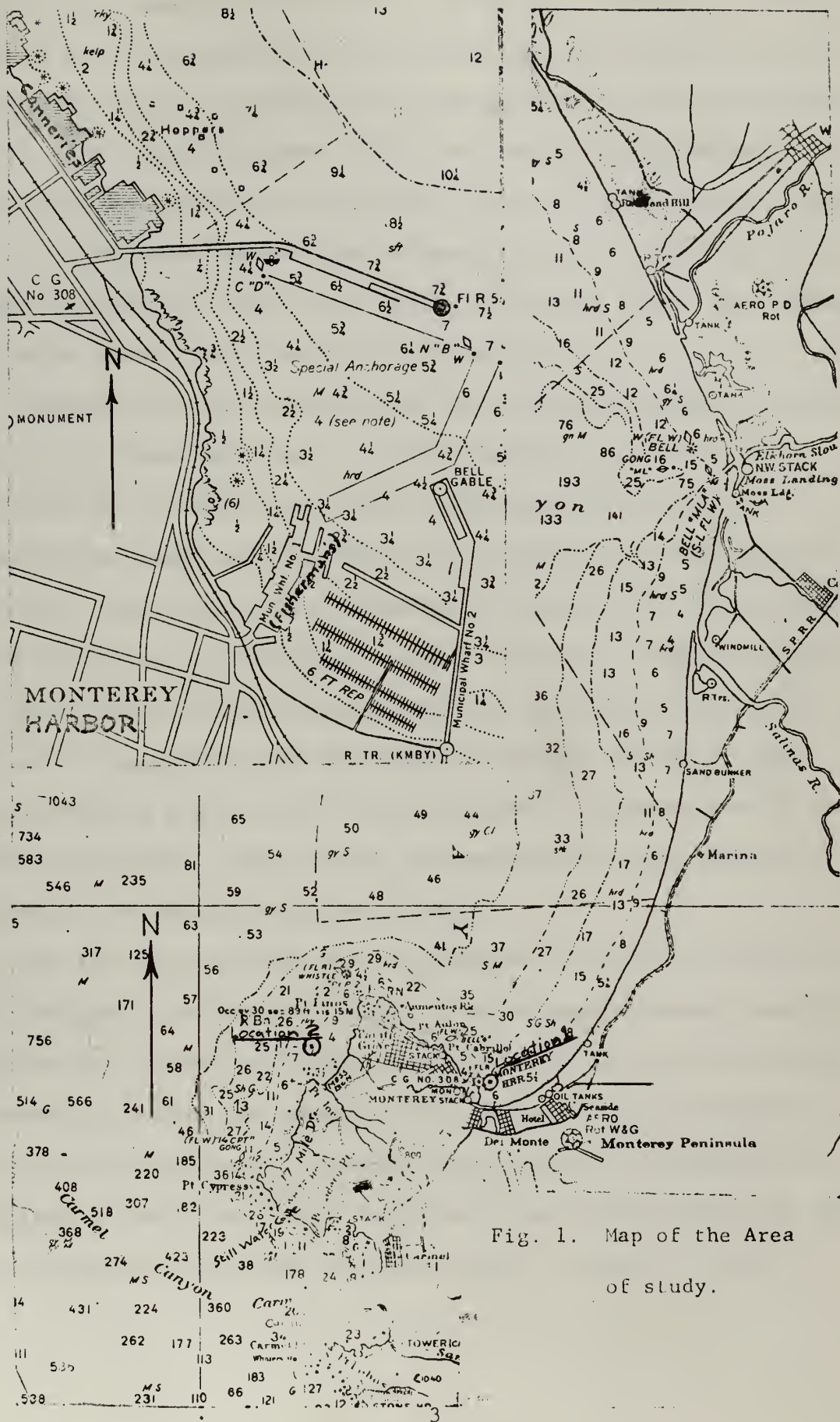
The research involved three separate studies. First, the occurrence, nature, and magnitude of notable storms and the damage they have wrought were documented. Second, from a study of weather maps and, in some instances, local observations, the synoptic conditions associated with these storms were described. Finally, attempts were made to determine if the synoptic conditions associated with these damaging storms were sufficiently unique to enable the forecasting of such storms in the future.

The specific area of the study was arbitrarily chosen as that part of the California coastline extending from Point Lobos northward around the Monterey Peninsula to Moss Landing, as shown in Fig. 1. This area was selected because some part of the coastline of the Monterey Peninsula is always exposed to approaching storms or storm waves from some given direction, and because useful descriptions of storms along this coastline are available in the local newspaper files.

Monterey Harbor itself is the most important part of this area by virtue of its improvements and economic value. Accordingly, the greatest attention was paid to incidents of damage there. As shown in the enlarged view of the harbor in Fig. 1, the breakwater protects the harbor



only from waves entering the harbor from directions west of north. The breakwater was completed in 1934, and prior to that time the harbor was completely at the mercy of any winds and waves with a northerly component. As will be shown, the breakwater does not provide sufficient protection from winds from north-northwest through north to northeast. The long pier, Municipal Wharf No. 2, is an open pile structure and provides no protection from winds or waves.





## 2. Procedure.

The only descriptive information available on the storms is to be found in the local newspapers, The Monterey Peninsula Herald [1], The Monterey Cypress [2], and The Monterey American [3], which are available back to 1910. The writer made a day-by-day search for the 50-year period from 1910 to 1960, and compiled a list of 39 occurrences of either wind- or wave-caused damage along the shoreline or in the harbor, or of notably high winds or large waves within the area of study. The complete list and a summary of it are given in Appendix I.

Although the writer believes that the newspapers contain a complete list of all storms and waves of any significance, the accounts themselves are quite subjective in their descriptions of the storms. Reported wind speeds and wave heights were probably gross estimates in many cases, and in others were probably not representative of the general conditions around the Peninsula. Storms of the same intensity may have been given unequal attention, depending upon the relative importance of the event in comparison with other news of the day, so that the news space devoted to a given storm is not necessarily representative of its relative importance. Nevertheless, the newspapers do give useful and interesting information about each storm.

From the list of storms that was compiled, the author selected for detailed study a smaller group which, from newspaper accounts, appeared to be the most significant. The original idea in this paper was simply to study the incidents of damage by storm waves arriving at the coastline from the open ocean. Therefore, the criterion first applied in making the selection was merely to select those instances where the waves were described as relatively large and clearly of oceanic origin and

where they caused some actual damage in the area studied. Six such occurrences were selected for the 50-year period. While some very significant storms were selected by this method, a number of occasions where heavy damage occurred within Monterey Harbor were not included. For this reason eight additional instances of damage were selected. Damage did not appear to be caused by waves from the open ocean in these cases, but nevertheless seemed to have been severe enough to warrant study. In six of the additional cases the newspaper accounts reported the dollar value of the damage. Where they did not, the author feels that damage can reasonably be assumed to have been comparatively light. The final list of 14 storms is believed to represent all cases in the original list of 39 storms which meet either the first criterion applied or where direct storm damage amounts to at least several thousand dollars and not all due to one single incident, such as damage to a single vessel.

Upon further study of the newspaper accounts of the 14 cases selected, it became apparent that these storms have been of two distinctly different types. The first is an open-ocean storm which produces storm waves or young swell of large size and long period. Most of the damage done in these storms is by the waves and is due to the surging of breakers to unusual heights up onto the coastline. The damage reported from these storms has taken the form of shoreline erosion; littering of golf courses, roads, and beaches with boulders and other debris; flooding of buildings and low areas; dynamic impact of the waves breaking against structures; and capsizing of boats. Erosion consisted of both sand removal from the beaches, which is largely temporary, and the permanent retreat of sea cliffs behind the beaches.

The second type of storm is a local storm of northerly winds within Monterey Bay which produces short-period storm waves. Damage caused by these storms is limited almost entirely to Monterey Harbor, and in contrast to the first type of storm damage has been restricted almost entirely to boats being broken loose from their moorings to drift into each other and into wharves, and finally to be driven onto the beach. Shoreline destruction has been comparatively unimportant. Damage by these storms is produced by a combination of strong onshore winds and accompanying waves. Wind is the predominant factor in this type of storm, whereas waves alone are the principal cause of damage in the first type of storm.

These two types of storms are treated separately throughout the thesis, and henceforth will be referred to as Open Ocean Storms and Bay Wind Storms, respectively. The storms selected for study are listed below according to date and type:

Open Ocean Storms

8- 9 Feb 1960  
 26 Oct 1950  
 23-29 Dec 1931  
 11-15 Feb 1926  
 27 Jan 1916  
 29-30 Apr 1915

Bay Wind Storms

23 Feb 1953  
 8- 9 Dec 1943  
 24-25 Dec 1942  
 20-21 Nov 1931  
 20 Feb 1931  
 29 Nov - 1 Dec 1923  
 27-28 Nov 1919  
 4 Oct 1912

The two types of storms required different analytical procedures. For the purpose of studying the characteristics of each storm and for the purpose of comparing storm intensities on the basis of wave conditions, the waves associated with each Open Ocean Storm were hindcasted for the Monterey area. For the two most recent storms, 1960 and 1950, six-hourly synoptic weather maps were available for analysis; but for the four earlier storms studies, 1931, 1926, 1916, and 1915, the only



maps available were the 24-hourly Northern Hemisphere Historical Series surface charts [4] . Each map sequence was analyzed for fetch areas beginning up to one week prior to the arrival of the storm waves at Monterey. Winds in the fetch areas were estimated mainly from plotted wind reports. The Sverdrup-Munk-Bretschneider (SMB) method [5] was used for making the wave hindcasts. Hindcasting worksheets for each storm are contained in Appendix II.

After hindcasting the significant wave height and period arriving in deep water off Monterey for each storm, the wave computations were modified for shoaling and refraction effects to obtain values of breaker height ( $H_B$ ) and wave run-up ( $R$ ) at two locations along the shoreline. These two locations are shown in Fig. 1 as Location 1, near the Monterey Harbor Breakwater, and Location 2, just offshore from Moss Beach. Both locations were selected because refraction diagrams for these two places were readily available. The Monterey Harbor location was also desirable in order to show wave conditions near the area where considerable damage has been inflicted. The Moss Beach location is representative in that it is exposed to storm waves from nearly all seaward directions. Both locations are hypothetical beaches with a simple 1:10 slope. This slope is an approximation of the compound slopes on the nearby actual beaches.

Refraction coefficients ( $K$ ) for the two locations were obtained from the refraction graphs that are shown in Appendix III. These graphs were prepared from the data obtained from a library of wave refraction diagrams constructed over a period of years by students in the Department of Meteorology and Oceanography at the U. S. Naval Postgraduate School. The refraction corrections were made by the method described in H.O. 234 [6] .

Breaker heights on the two beaches were computed from the University of California graph of breaker-height index [7], which gives  $H_B$  as a function of beach slope and initial wave steepness,  $H_0'/T^2$ , where  $H_0'$  is the unrefracted deep-water wave height (i.e., height a shoal-water wave would have in deep water if it had not been refracted), and  $T$  is the wave period. Breaker heights were determined for the purpose of comparison with reported wave heights when the latter appeared in news accounts. It was assumed that the wave heights reported in news accounts were observed along the shoreline by casual observers, and were in fact the heights of the breakers.

Wave run-up, the vertical height above the still-water level to which water from a breaking wave will rise on a sloping beach, a sea-cliff, or on the face of a structure, was computed from curves using the same variables as in the breaker-height calculations. The wave run-up curves were developed by Saville from his laboratory studies [8]. Wave run-up was considered to be of particular importance here because it was felt that this parameter provides the best index of the capability of waves from Open Ocean Storms to do damage to the shoreline. One of the principal purposes in hindcasting the waves from the Open Ocean Storms was to provide a method of comparing the several storms. When the wave run-up is multiplied by the storm-wave duration, a quantity defined here as the "Damage Potential" of a storm is obtained which is used herein as a basis for making an objective comparison of the intensities of the individual storms from the standpoint of their damage capabilities. Damage Potential was computed for the Monterey Harbor location only.

In order to give the true run-up value on the shoreline, the computed run-ups were superimposed on the Monterey Harbor tides which in

turn are referred to Mean Lower Low Water (MLLW). Accordingly, the run-up heights that are presented herein were all measured above that datum plane and were used in computing the Damage Potential of each storm. Meteorological tides, which are considered to be small on this coast, were not taken into account.

A detailed study of the Bay Wind Storms proved to be more difficult, primarily because of the lack of synoptic wind data due to the relatively local nature of the storms and to their short duration. Here again, only for the two most recent storms, 1943 and 1953, were six-hourly synoptic maps available, and even these were not completely satisfactory because of the very short duration of the wind storms. Only the 24-hourly Northern Hemisphere Series was available for the earlier storms; accordingly, the wind and wave data are poor. Because of the short duration of the storms, many and often most of their features were lost in the 24 hours between maps. To further complicate the problem, it was discovered after the study began that actual wind observations in the vicinity of Monterey for the dates of the storms do not exist except for the storm of 1953. Weather observations for Monterey during that storm were taken at the U. S. Naval Air Facility located at the Monterey Airport shown in Fig. 1. Because of the interval between maps and the lack of observed serial data, winds had to be obtained from geostrophic values and from newspaper reports, unless otherwise noted.

It appeared from the news accounts that the destructive winds in these storms ranged in direction between northwest and northeast.

Accordingly, because of the shape and orientation of the Bay, the waves generated could be produced over a maximum fetch of only 25 nautical miles, the distance from Monterey Harbor to the city of Santa Cruz at the north end of the Bay. This means that the largest waves generated by strong winds are always fetch-limited. For example, according to the SMB curves, a steady 30-knot wind must blow for only about 3-3/4 hours before the 25-nautical-mile fetch becomes limiting. Therefore, wind direction and speed were considered sufficient to compare intensities of these storms with respect to the damage that they produced.

After both types of storms were analyzed, as described above, the weather maps were again consulted, this time for the associated synoptic weather situations. The synoptic situations were first described for each storm, and then attempts were made to find clues that would enable the forecasting of damaging storms. Upper-air charts were available only for the storms of 1950 and later; accordingly, surface maps were relied upon in order that comparisons between storms could be made on an equal basis. 500-mb charts were used as an aid in describing the patterns for the more recent storms.

Two distinct types of synoptic weather situations were immediately apparent, one for each of the two types of storms previously described. The storms were also grouped by weather types using the North American Weather Types of the California Institute of Technology (CIT) [9] and as modified by Elliot [10]. This procedure also yielded only two basic significant patterns, as will be discussed subsequently.

In the case of the Open Ocean Storms, storm tracks and other meteorological features were then compared with composite tracks given by Elliot with the hope of discovering deviations that might aid in the

prediction of these storms.

In the case of the Bay Wind Storms, the synoptic conditions were compared with those described in other studies of California winds, namely that of Lockhart [11] and of Sergius and Huntoon [12] .

Throughout this paper all distances are given in nautical miles and all times referred to are Pacific Standard Time, unless otherwise stated. When Greenwich Mean Time is used, the indicated time is followed by the time-zone designator "Z."



### 3. Open Ocean Storms.

This section includes a descriptive account abstracted from the newspapers of each of the six selected Open Ocean Storms, along with wave hindcasting analyses for each storm. The hindcasts include the significant wave height ( $H_0$ ) and period (T) for deep water off the Monterey Peninsula. Tabulated data from which the curves are drawn are given in Appendix IV. Based upon these descriptions a comparison of these storms as to their relative intensities is made.

$H_0$  and T, breaker height ( $H_B$ ), and wave run-up (R) as well as the tides are all plotted against time for Monterey Harbor in Figs. 2a through 7a. Moss Beach values of  $H_B$  and R are shown similarly in Figs. 2b through 7b. The graphs of R values for the Harbor show the computed run-up relative to the still-water level by a dashed curve, and the run-up superimposed on the tides, or the actual run-up, by a solid curve. The actual run-up is considered here to be the most suitable measure of the damage capability of the storm because the damage from this type of storm is principally in the form of coastline erosion and overtopping of seacliffs.

Storm of 8-9 February 1960: This storm struck Monterey about 0730 on 8 February with gusts to 45 mph reported at the Monterey Airport and sporadic torrential rains. Large waves were first reported during the night of 8-9 February with maximum heights occurring at approximately 0800 the following morning at the peak of a five-foot tide. Breaker heights of 30 to 40 feet and gusts of 40 mph were reported by observers. The maximum gust officially reported on the hourly Aviation Weather Reports at the airport, however, was 33 knots at 1000 on 8 February. Large waves continued throughout the 9th, subsiding by the morning of

the 10th. Damage included the destruction of a \$75,000 pier at Stillwater Cove near Pebble Beach. In addition, numerous small craft were swamped, capsized, and beached in the harbor; large boulders were strewn over Seventeen-Mile Drive and the adjacent golf courses; portions of the golf courses were flooded by sea water; the shoreline near Point Joe and at several other places around the Peninsula was heavily eroded; and shoreline property around the Peninsula suffered numerous instances of minor damage. At Point Aulon a man was swept off a rock by a large wave and was drowned. At the Ocean View Hotel on Cannery Row sea water smashed through a third-floor window and damaged the interior of a room.

The hindcasted wave data for this storm are shown in Figs. 2a and 2b. It is interesting to note, from the figures, that the maximum breaker height occurs later than the maximum deep-water wave height, and that the maximum run-up occurs even later and near the time when the largest waves were reported near the shoreline. The lag in maximum  $H_B$  is attributed to the fact that waves arriving at 0400, 9 February, are from a somewhat more northerly direction and thus undergo less refraction than the earlier arriving waves which have a more southerly direction of approach. The lag is made even greater due to an increased  $T$  shortly after the time of maximum  $H_0$ , but the lesser refraction at the time of largest  $H_B$  is the principal cause. An even greater lag behind the time of maximum  $H_0$  exists in the maximum run-up. This is because of the addition of the tides which are at their highest at 0800 on 9 February.

Observed winds at the Monterey Airport averaged approximately 15 knots over the 8th and 9th of February, and accordingly were not significant in the analysis of this storm. However, because of a probable sheltering effect of the Monterey Peninsula to southwest winds,

the author believes that observations of southwest winds at the Airport are not entirely representative and that the winds may have been stronger over the adjacent open ocean.

Storm of 26 October 1950: This storm seems to have been more of a spectacular display of surf around the Monterey coastline than a storm causing significant wave damage. Considerable damage did occur ashore from falling trees, power lines, etc., but, as noted in the newspapers, there was surprisingly little damage to the waterfront.

While the local storm hit the afternoon of the 26th with strong winds, the large waves were reported to occur the night of the 26th and the morning of the 27th. Based upon a wave hindcast utilizing hourly surface winds at the Airport in conjunction with six-hourly synoptic surface weather maps, maximum wave heights occurred somewhat earlier; in fact about 1630 on the 26th as shown in Figs. 3a and 3b. However, the duration of large waves was quite short. While no specific evidence confirms it, the writer feels that there is a close relationship between the duration of the very large waves and the amount of damage incurred.

In this storm very few instances of specific damage were reported. One to two feet of sand were removed from Monterey Beach just north of the Municipal Wharf No. 2. Several pilings on the two wharves were torn away, and a door was torn off a boat locker in Pacific Grove. In Carmel waves crossed Scenic Drive, which runs along the ocean shore above the beach at a height of about 25 feet above mean sea level. At Carmel Point on Point Lobos an automobile, with its occupant, was picked up bodily by one very large wave and set down again, fortunately right side up. Waves also crossed Ocean View Boulevard in Pacific Grove, and in the Lighthouse Reservation in the vicinity of Point Pinos. Along the



shoreline the waves were reported moving 50 feet or more inland from the usual high-water marks. Waves were also reported breaking completely over the rocks at Lovers' Point, some 50 feet in height.

The discrepancy between observed and hindcasted times of maximum wave heights may be the result of a possible misinterpretation of the weather maps for decay distance from the fetch area to Monterey.

Storm of 23-29 December 1931: This was quite a widespread storm, covering most of the California coast and of several days' duration. The storm, in addition to high winds and waves, brought a record rainfall to the Monterey Peninsula for the six-day period. On the 24th of December high winds were reported to have caused several fishing boats to be beached inside the Harbor. This is somewhat contradictory to the reported wind direction of southwest, since a southwest wind is from offshore in the Harbor and is not likely to blow vessels ashore there. However, from the hindcast it appears that the swell waves were from the northwest and as such probably contributed appreciably to the boat damage.

More boats were reported capsized and sunk at their moorings on the 25th. As shown in Fig. 4a, the highest breakers in the Harbor occurred on that date. The same day, the breakers near the wharves washed out a considerable amount of fill and reached the main Southern Pacific railroad tracks, to which they inflicted slight damage. By the 26th both the wind and waves had become more northwesterly. During the night of the 26th and the morning of the 27th the deep-water waves were at their greatest heights, as were the breakers in the more exposed locations (see Figs. 4a and 4b). During this phase most of the damage to the shoreline occurred.

A summary of damage follows (except for fishing-fleet damage, all occurred on the 26th or 27th):

1. Two hundred feet of loading pier were torn out at one cannery, amounting to \$20,000. An additional \$3,000 was incurred in lesser damage to other canneries. The back of the Ocean View Hotel in the same area received \$1,000 damage.
2. Twenty-five thousand dollars worth of fishing boats and equipment was lost.
3. Washout of new fill by the railroad station occurred.
4. Boardwalk and outer end of Del Monte Bathhouse pier were destroyed.
5. Seventeen-Mile Drive near Fan Shell Beach (adjacent to Point Joe) was badly torn up by breakers and littered with boulders. Surf-driven logs battered down the door of the Country Club Bathhouse in the same area. A portion of the golf course was flooded with salt water.
6. Ocean View Boulevard near Point Pinos was impassable because of the litter of logs and boulders.
7. Undermining of railroad tracks along the shoreline in Pacific Grove occurred in several areas.
8. From the Harbor northward to the Salinas River mouth the shoreline receded an average of about five feet.

The total of damage attributed to the storm waves was conservatively estimated at \$50,000.

Storm of 11-15 February 1926: This was an extremely violent and widespread storm that struck all of the southern half of California. Very large waves were reported all along the coast with the exception of

the north side of the Monterey Peninsula. Wave direction varied from 250 degrees true with the early arriving waves to 270 degrees true as the waves reached their maximum height. No damage from waves whatsoever was reported in Monterey Harbor even though, from newspaper accounts, the storm waves battering the coast were some of the largest ever observed. On the south side of the Peninsula large waves were apparently observed, as it was reported that Carmel Beach was completely under water. No other mention of damage was made, however. At Moss Landing a pier was damaged to an unreported extent about the 14th or 15th. Considerable damage was reported at Santa Cruz on the morning of the 12th, and, while Santa Cruz is outside of the area of this study, the date of heavy damage there does tend to confirm the wave hindcast at Monterey Harbor.

Only one relatively small but intense wind area could be located on available 24-hourly weather maps that was capable of generating waves which, during the duration of the storm at Monterey, would arrive there with a height greater than five feet. This situation contradicted the newspaper accounts describing such widespread occurrences of large waves and no satisfactory explanation was apparent. Figs. 5a and 5b show what is perhaps the most noteworthy feature of the wave hindcast at Monterey -- the very short duration of the large waves. Here again it seems that duration may be a factor in determining the degree of damage. However, in this case, waves apparently were not so high as in other storms studied.

Storm of 27 January 1916: This storm caused no damage at Monterey itself nor was any damage reported on the west or south sides of the Peninsula. However, considerable damage was inflicted at Moss Landing,

including the destruction of a sturdy steamship pier there. Santa Cruz was also hard hit. According to the wave hindcast for this storm, shown in Figs. 6a and 6b, it is reasonable to assume that large waves were present around the Monterey Peninsula and that at least considerable erosion of the beaches occurred. Reports of such damage were not as likely to have been made since these areas were rather isolated and little populated in 1916.

Considering the direction of approach of the swell waves, northwest and later west-northwest (see Appendix IV), it is rather surprising that no damage was reported in Monterey Harbor. However, winds during the storm were reported as southwest and of gale velocity by the newspapers. If these winds remained as such throughout the storm, it is possible they had a flattening effect on the arriving swell. Such a wind effect was not considered in the hindcast.

Storm of 29-30 April 1915: Wave damage from this storm was quite severe, especially when one considers the wave heights and particularly the run-ups in comparison to other Open Ocean Storms. This storm stands among the three most disastrous in the 50-year period. The most significant feature of the storm which is unique is that, according to the hindcast (Figs. 7a and 7b), the swell waves came from the northwest throughout the duration of the storm. In addition, winds in the Harbor area were reported to prevail from the northwest. This condition resulted in some very large breakers hindcasted for the Harbor area (Fig. 7a), and the resulting damage bears this out.

Generally the news accounts and the hindcasts agree quite well for this storm. The storm was reported to have commenced early in the morning of the 29th, as the hindcast shows, and most of the damage was



inflicted the afternoon of the 29th.

The reader should note that in this particular storm the waves in the Harbor (Fig. 7a) were approximately as large as those on the usually more exposed Moss Beach (Fig. 7b). This phenomenon, which is uniquely associated with a northwest direction of wave approach, is the result of the waves experiencing very little refraction as they approach the Harbor from deep water; whereas waves approaching Moss Beach from deep water experience more refraction and thus diminish in height more than if they had come from a westerly or southwesterly direction.

Damages incurred during the storm were as follows:

1. The city wharf (now Fishermen's Wharf) was buckled and pilings were lost. Fish sheds were blown off the wharf by strong winds.
2. Some of the pilings supporting the canneries along Cannery Row were loosened and were banging against the other pilings, weakening the structures.
3. As many as 100 boats of all sizes (mostly very small) were washed ashore and some were badly damaged.
4. Railroad yards were littered by debris thrown ashore by the breakers.
5. A boat valued at \$4,500 was sunk at Point Lobos.

The total damage was estimated at about \$30,000 to \$40,000. The havoc created by this storm is graphically illustrated in Fig. 8, which is reproduced from a photograph found in the historical files of the Monterey Public Library.

Summary of Wave Conditions Accompanying Open Ocean Storms: A summary of the important wave characteristics of the storms just discussed, compiled from Figs. 2 through 7, is presented in Table 1. Also included are



<u>Storm</u>	Feb 1960	Oct 1950	Dec 1931	Feb 1926	Jan 1916	Apr 1915
<u>Deep Water</u>						
Max $H_O$	37	34	23	21	24	26
T	15.0	15.4	11.7	15.4	11.7	12.9
$\psi_o$	280	270	230	270	270	315
Duration > 15'	35.5	9.0	30.5	8.0	15.5	21.0
Date/Time	08/2200	26/1630	27/0400	12/1300	27/0400	29/1600
<u>Monterey Harbor</u>						
Max $H_B$	26	21	16	15	17	30
Max R	19	14	16	15	14	19
Date/Time	09/0600	26/1030	27/0130	12/1630	27/1000	29/2130
<u>Moss Beach</u>						
Max $H_B$	46	44	34	31	25	34
Max R	22	20	20	17	14	14
Date/Time	09/0330	26/1630	27/0200	12/1230	27/0300	29/1600
Total Damage (actual)	\$85,000	\$1,000	\$ 50,000	\$5,000	\$10,000	\$35,000
Total Damage (1960 equiv.)	\$85,000	\$1,300	\$128,000	\$8,500	\$14,000	\$49,000
Damage Potential	675	126	488	120	217	400

Table 1. Summary of Characteristics of Important Open Ocean Storms.

$\psi_0$  (direction in degrees true from which deep-water waves approach), estimated total damage in dollars, and the computed Damage Potential for Monterey Harbor.

The first four items presented are a measure of the general dimensions of the storm.  $H_0$  (significant wave height in deep water) is given as the maximum that was hindcasted for the storm. Duration represents the length of time in hours during the storm that  $H_0$  was greater than 15 feet.  $T$  is the significant wave period in deep water at Monterey associated with the maximum  $H_0$ . The values given for  $\psi_0$  represent wave direction at maximum  $H_0$  and were obtained directly from the hindcast worksheets in Appendix II. Wave run-up is given for the Monterey Harbor location as the height above the still-water level superimposed on the tides. No tides were available for Moss Beach, thus  $R$  at that location represents the run-up relative to still-water level only. Times of occurrences of maximum  $H_0$  in deep water and maximum  $R$  in the Harbor and at Moss Beach are also presented for comparison.

According to a statistical wave study from Scripps Institution of Oceanography [13], the deep-water wave height at a selected point off the coast near Monterey Bay (37.5N and 123W) is greater than 15 feet 0.2% of the time. This was found to correspond roughly to the percentage of time in which the storms under study in this paper have occurred over the 50-year period. It was on this basis that the criterion of  $H_0$  greater than 15 feet was arbitrarily selected in order to define duration.

The dollar damage is given both as the estimated actual value in the year it occurred and as an adjusted value based on price-index changes [14] over the years, using 1960 as the base year. The dollar-damage estimate is as reported by the newspapers except for the storms of

October 1950, February 1956, and January 1916. Damage from these storms is given as the author's own subjective estimate, based upon the descriptive newspaper accounts.

If Damage Potential is assumed to be a true measure of the storm intensity at a given location, then it is evident from Table 1 that at Monterey Harbor the storm of February 1960 was the most severe during the 50-year period. Although tides were not known exactly for the Moss Beach location, they may reasonably be assumed to be approximately the same as for Monterey Harbor. If this is the case, then run-up superimposed on the tides is also greatest for this storm at Moss Beach and so also is the Damage Potential. A study of the curves of wave run-up above still-water level for all other storms for both locations reveals that, using the same argument regarding tides at Moss Beach, the resulting Damage Potential values for Moss Beach would all remain in the same relative order as for Monterey Harbor. Thus, on the basis of Damage Potential, the February 1960 storm was the most severe, followed by the storms of December 1931, April 1915, January 1916, October 1950, and February 1926 in order of decreasing severity.

From the standpoint of dollar damage only (adjusted to 1960), the storm of December 1931 was the worst, followed by February 1960, and then, as before, April 1915, January 1916, October 1950, and February 1926. The most apparent reason, and in the author's opinion the most valid, for the greater damage in the 1931 storm in spite of a lower Damage Potential than in 1960, is simply that in 1931 Monterey Harbor was not protected by a breakwater.

At the other end of the damage scale, the small dollar-damage losses experienced in the October 1950 and February 1926 storms are quite in keeping with the low Damage Potentials of these two storms. It is

interesting and significant to note that in the 1950 storm the maximum deep-water wave height was only three feet less than in the February 1960 storm; however, damage in the earlier storm was relatively insignificant, adding weight to the argument of Damage Potential as a measure of the intensity of the Open Ocean Storm.

Another characteristic of the Open Ocean Storm is illustrated by comparing the times of occurrence of maximum deep-water wave height and maximum wave run-up at Monterey Harbor. It was shown that the time difference actually depends on the significant wave period, the direction of approach of waves in deep water, and the astronomical tides. Both positive and negative time differences occurred, amounting to as much as eight hours.

As pointed out earlier, damage to the shoreline and on the coast is characteristic of the Open Ocean Storm. Shoreline damage apparently is caused principally by large run-up, and since  $R$  increases markedly with an increase in period for a given  $H_0$ , it is only the large Open Ocean Storms, in which  $T$  is large, that can do serious damage to the shoreline.

The frequency of this type of storm works out to be about one every 8.3 years. Saville [15] analyzed weather maps for a 12-year period for waves in excess of 20 feet at Half Moon Bay, California, some 50 miles north of Monterey, and obtained a frequency of one such storm every four years. However, he subjectively modified his results based upon some Scripps hindcasted data for the same general area, and concluded that a frequency of such storms once every eight to ten years is more likely. This present study for Monterey compares well with his results.

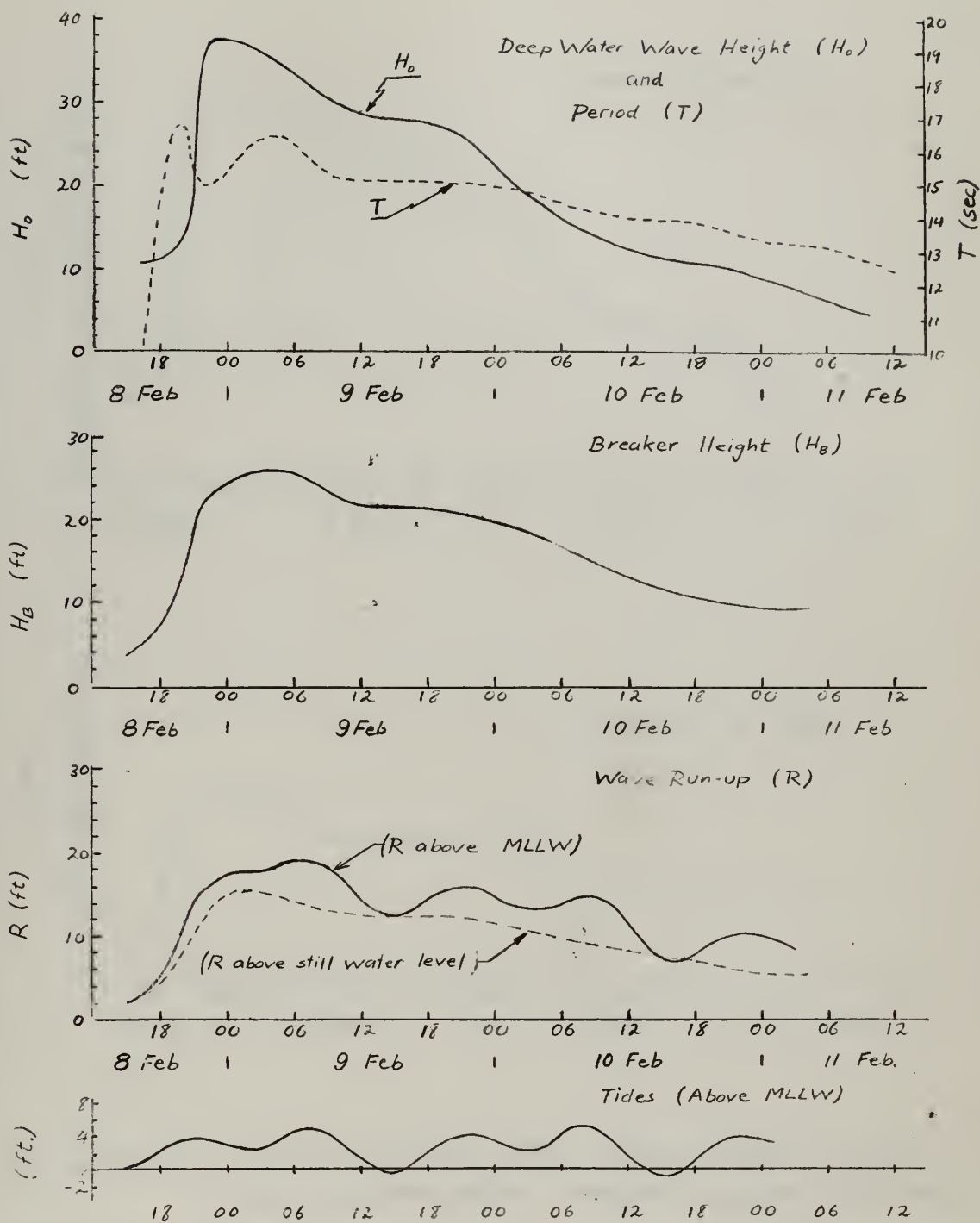


Fig. 2a. Storm of 9 February 1960. Wave height and period in deep water; breaker height and wave run-up in Monterey Harbor. Highest waves were reported at 0800 9 February.



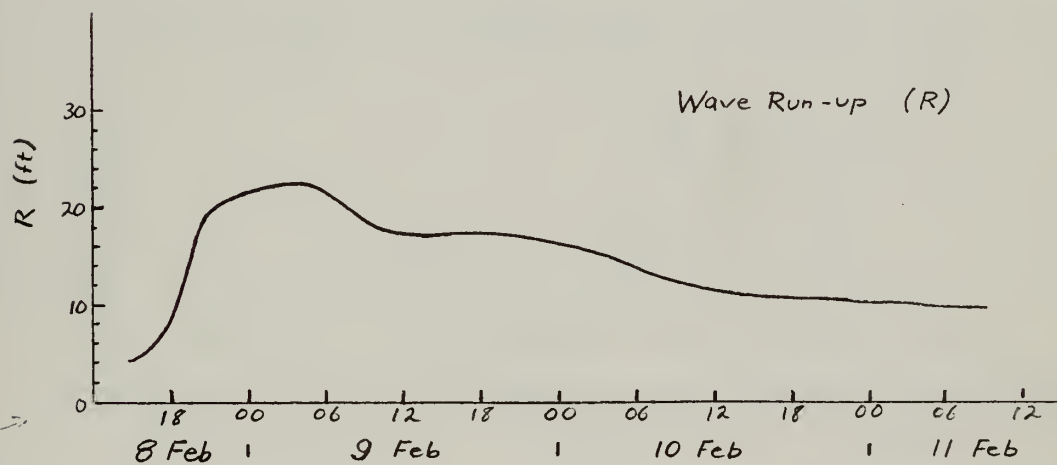
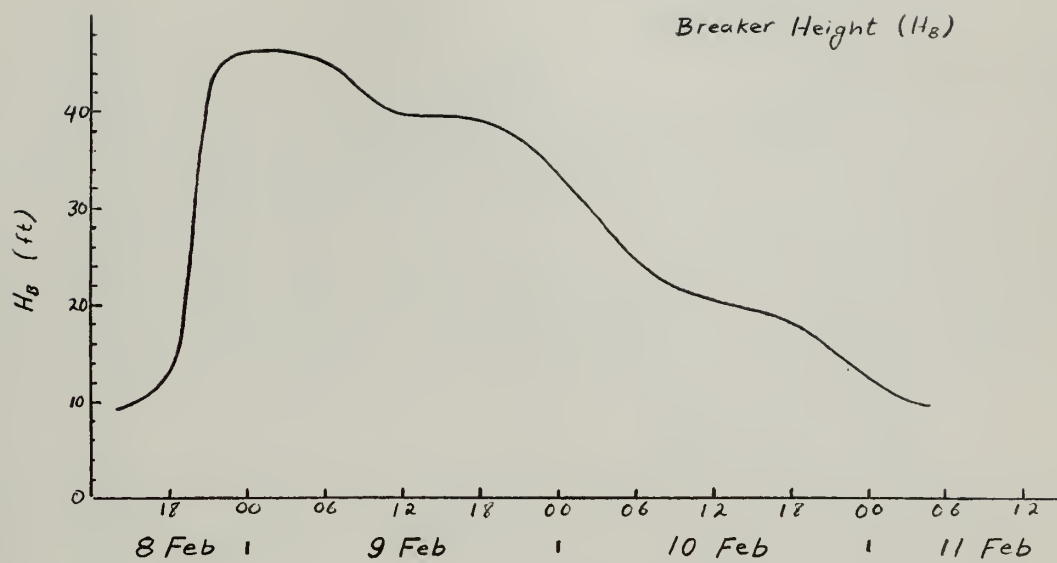


Fig. 2b. Storm of 9 February 1960. Breaker height and wave run-up near Moss Beach. Heights are above still-water level.

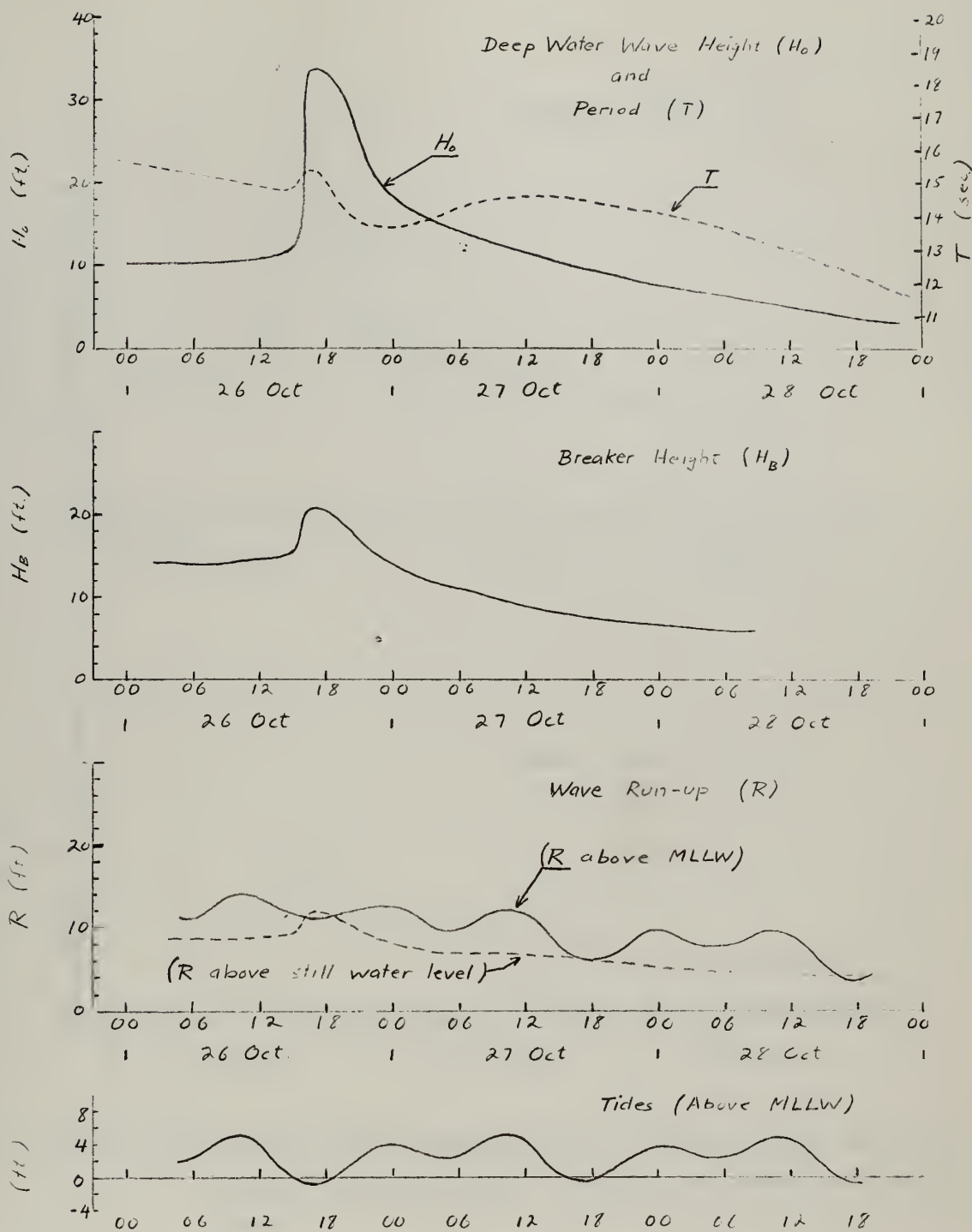


Fig. 3a. Storm of 26-27 October 1950. Wave height and period in deep water; breaker height and wave run-up in Monterey Harbor. Highest waves were reported during the night of the 26th and morning of the 27th.

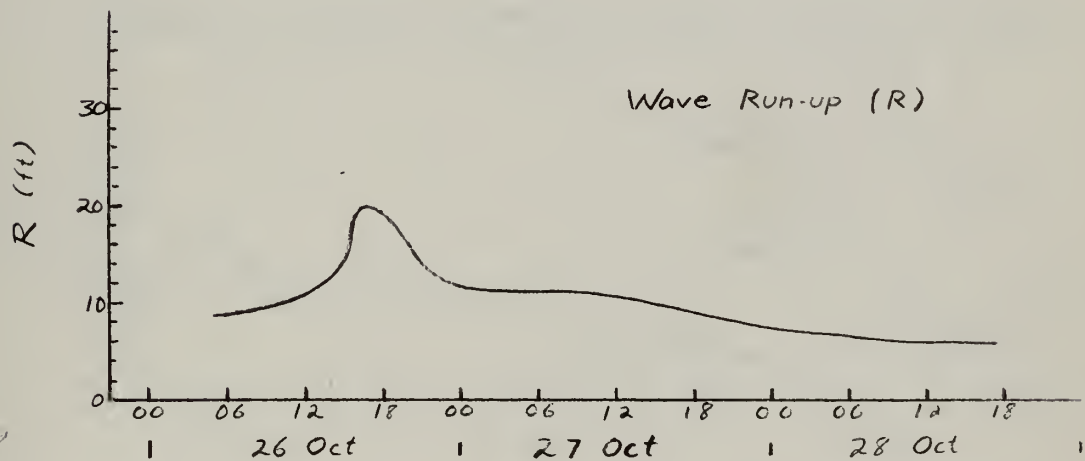
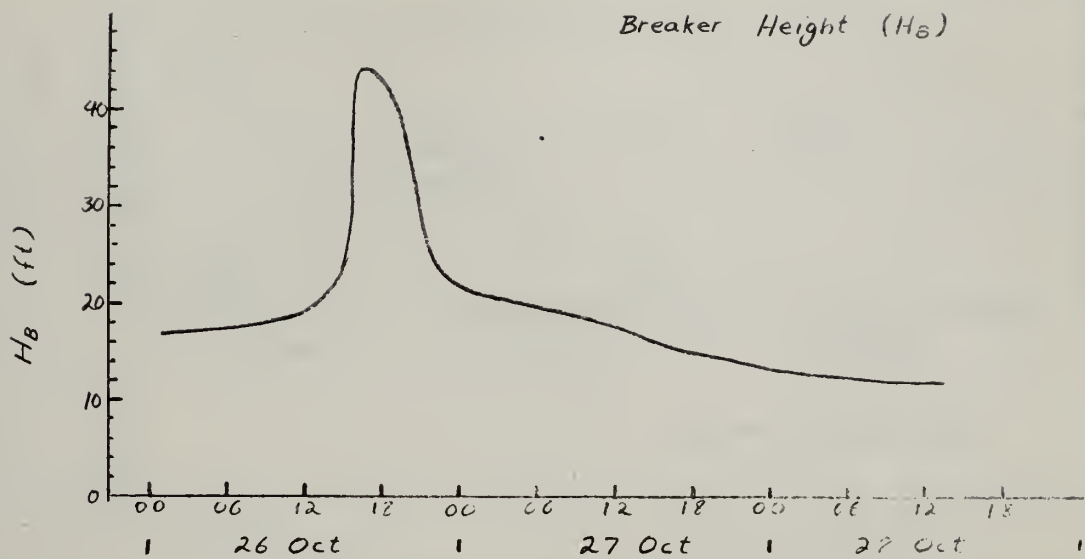


Fig 3b Fig. 3b. Storm of 26-27 October 1950. Breaker height and wave run-up near Moss Beach. Heights are above still-water level.



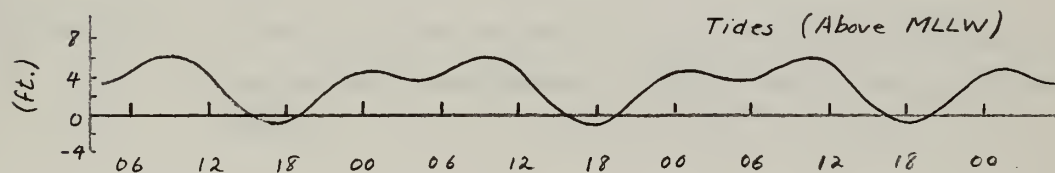
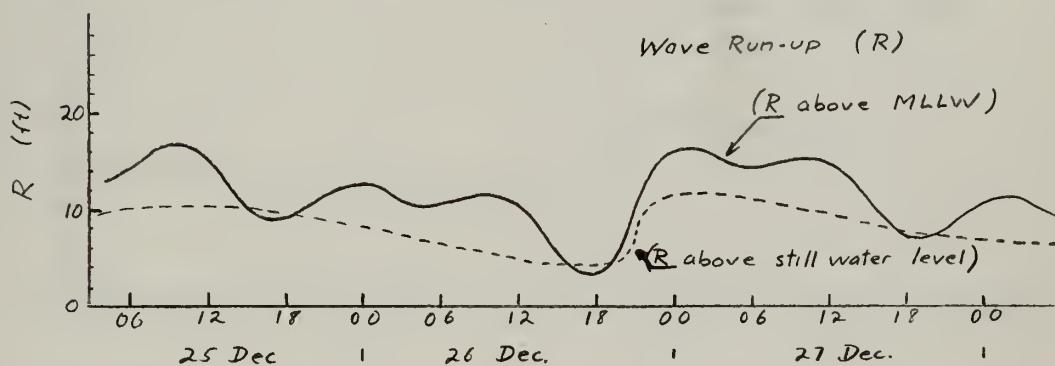
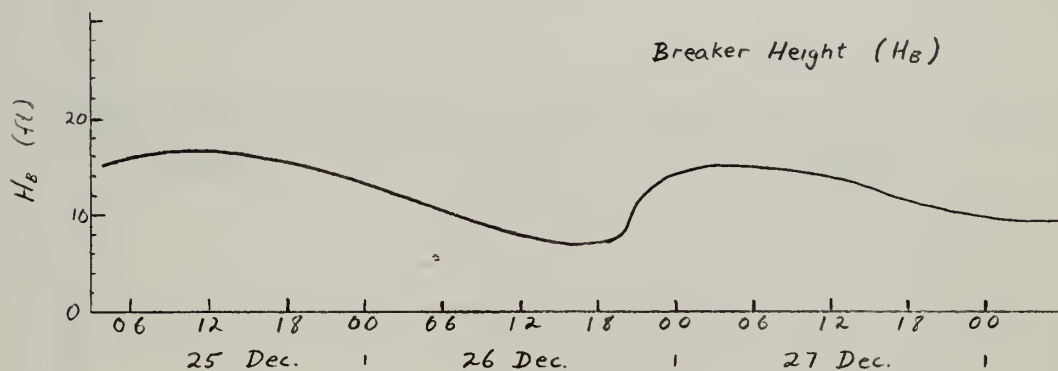
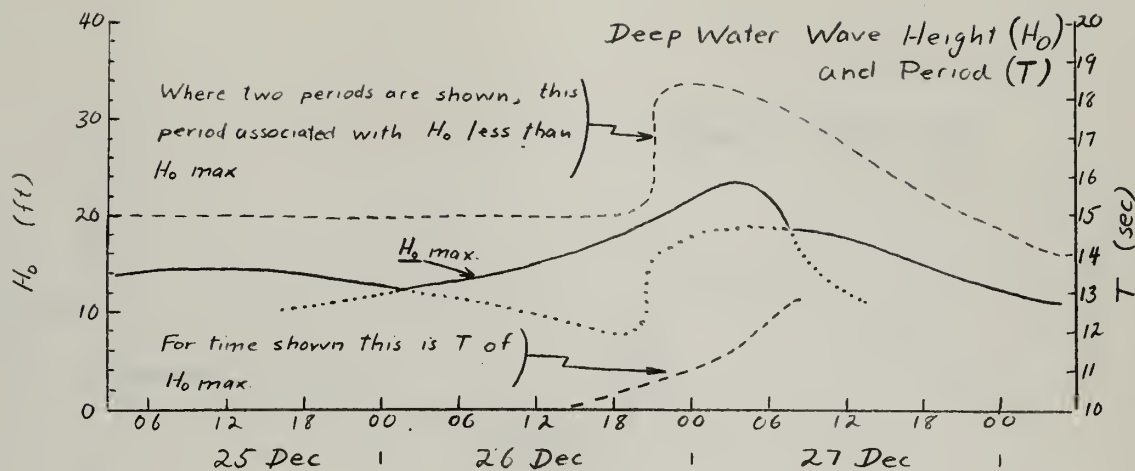


Fig. 4a. Storm of 23-29 December 1931. Wave height and period in deep water; breaker height and wave run-up in Monterey Harbor. Highest waves were reported the night of the 26th and morning of the 27th.

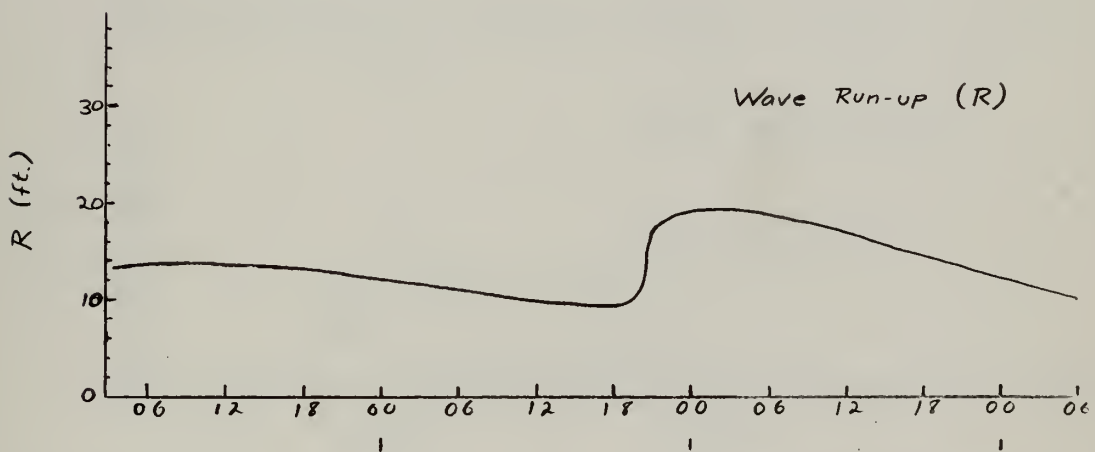
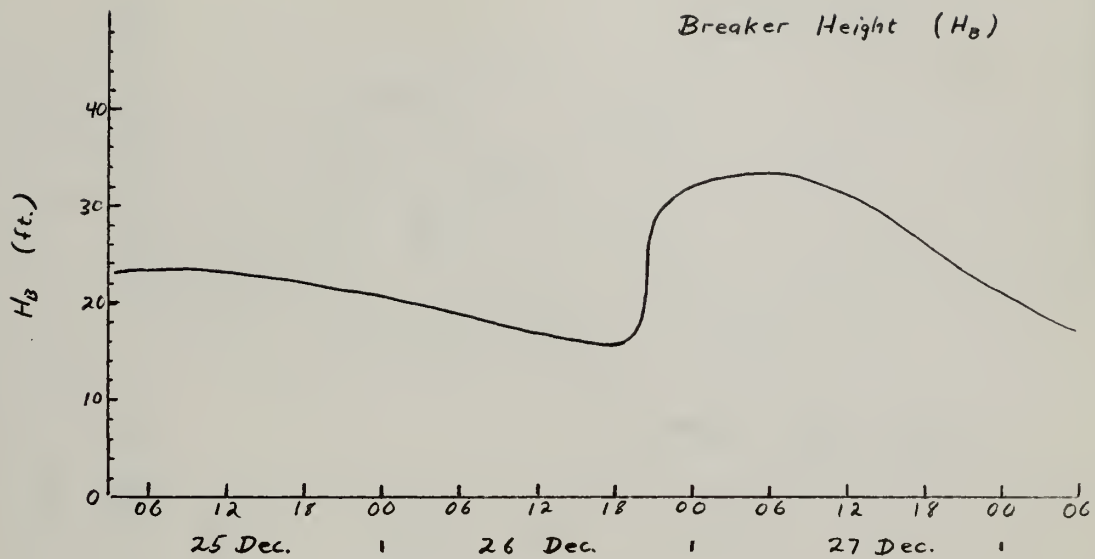


Fig 4b Fig. 4b. Storm of 23-29 December 1931. Breaker height and wave run-up near Moss Beach. Heights are above still-water level.

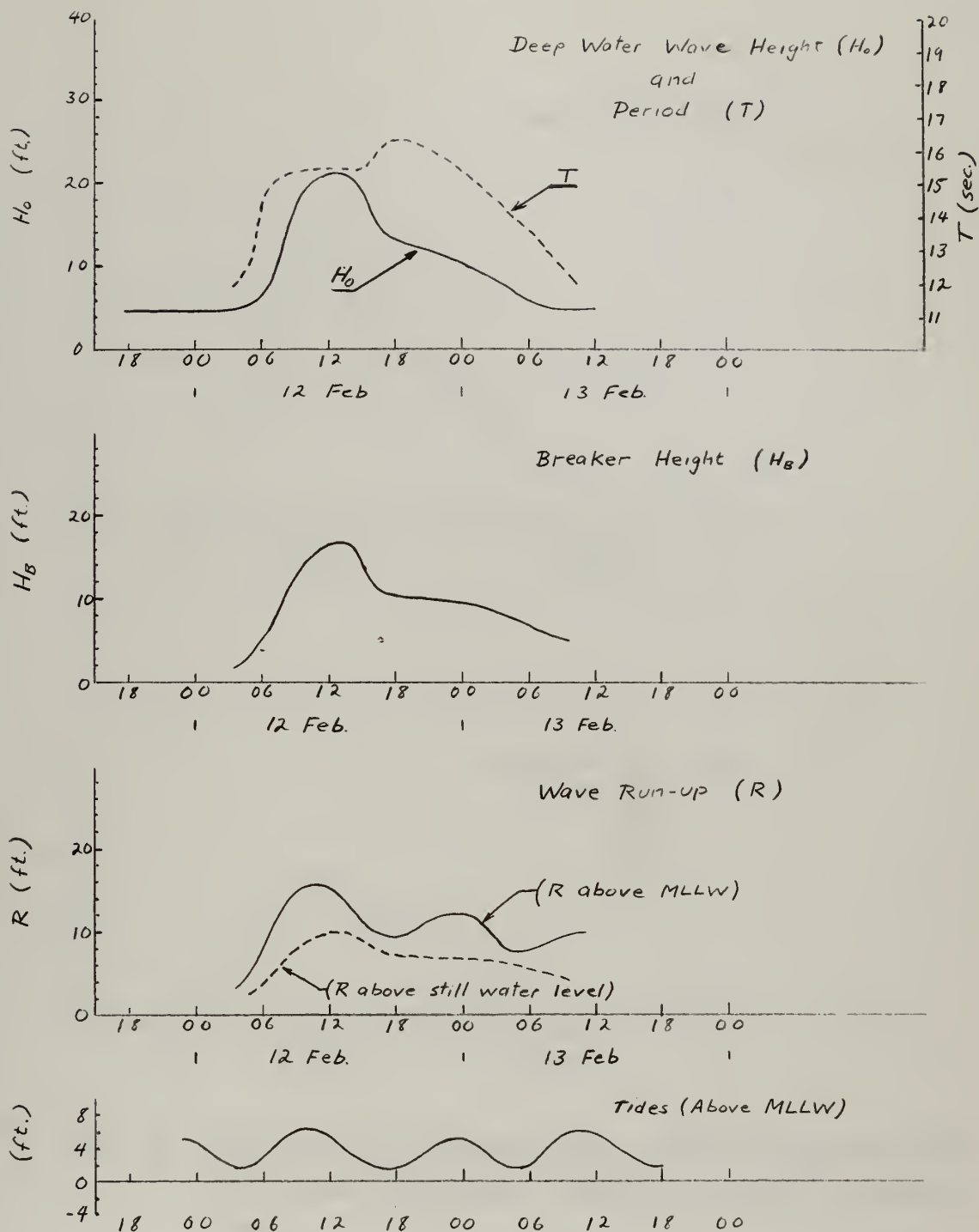


Fig. 5a. Storm of 11-15 February 1926. Wave height and period in deep water; breaker height and wave run-up in Monterey Harbor. Time of highest waves was not reported.

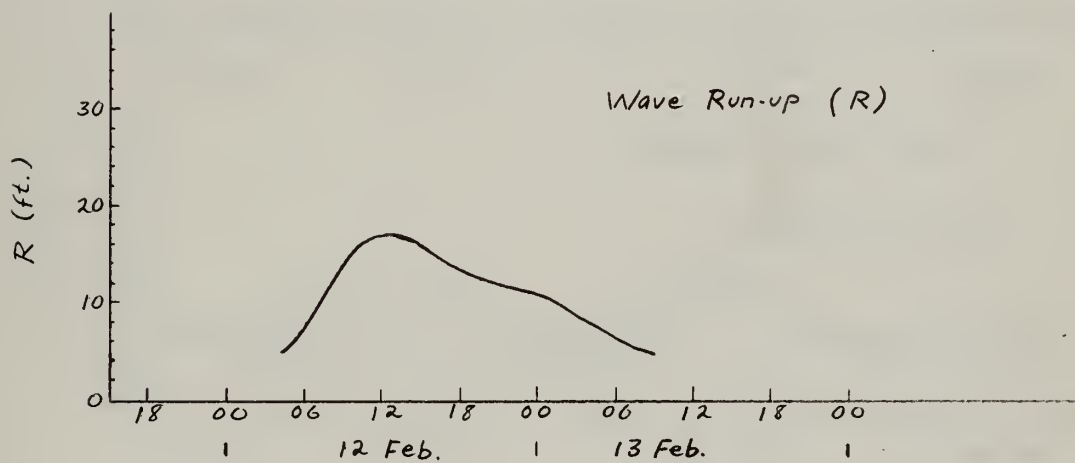
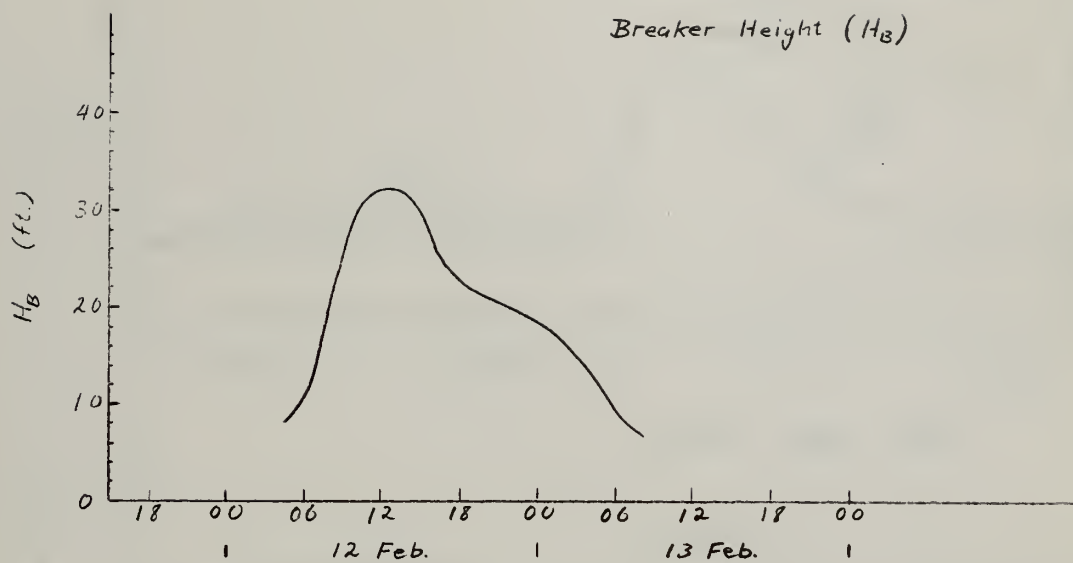


Fig 5b

Fig. 5b. Storm of 11-15 February 1926. Breaker height and wave run-up near Moss Beach. Heights are above still-water level.



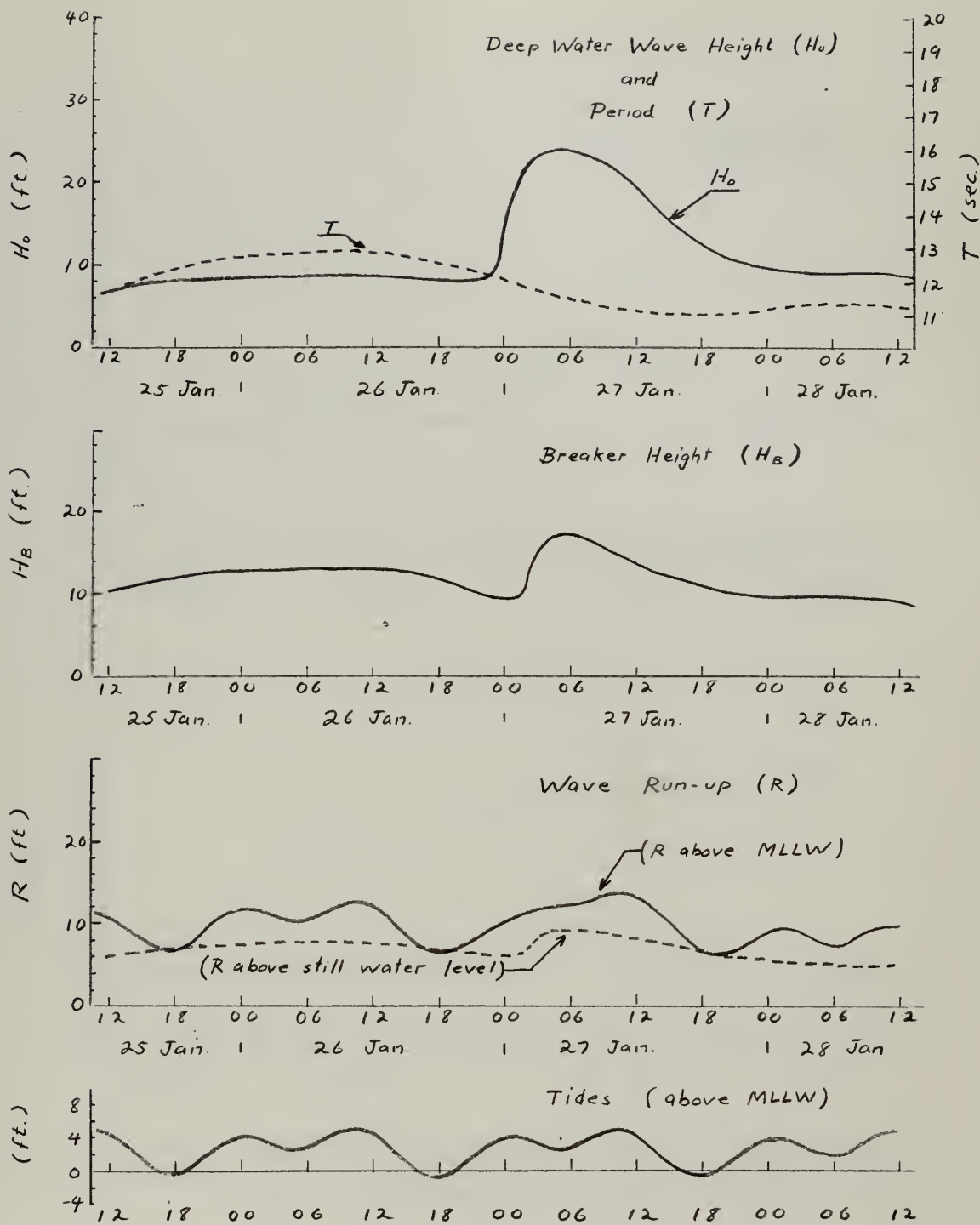


Fig. 6a. Storm of 27 January 1916. Wave height and period in deep water; breaker height and wave run-up in Monterey Harbor. Time of highest waves was not reported.

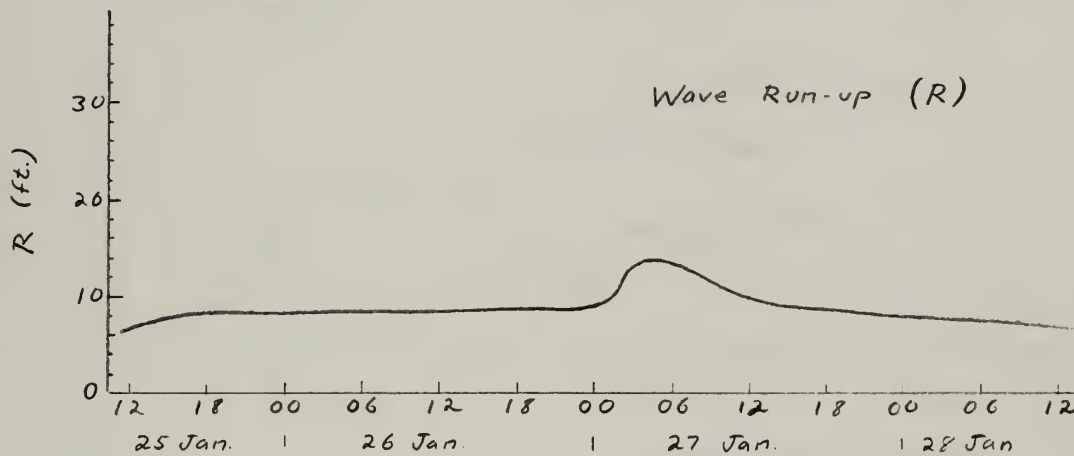
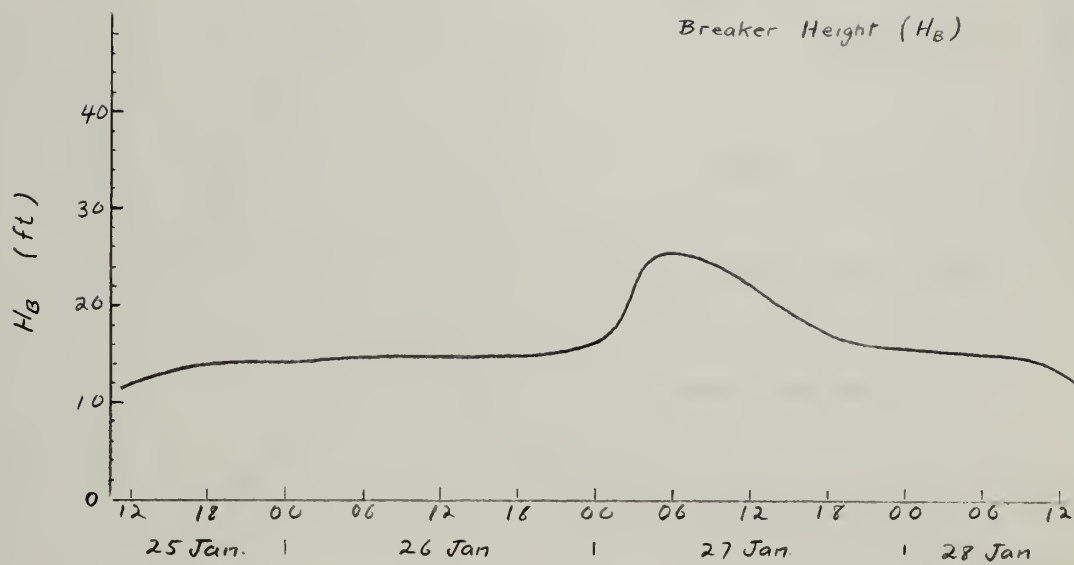


Fig. 6b. Storm of 27 January 1916. Breaker height and wave run-up near Moss Beach. Heights are above still-water level.

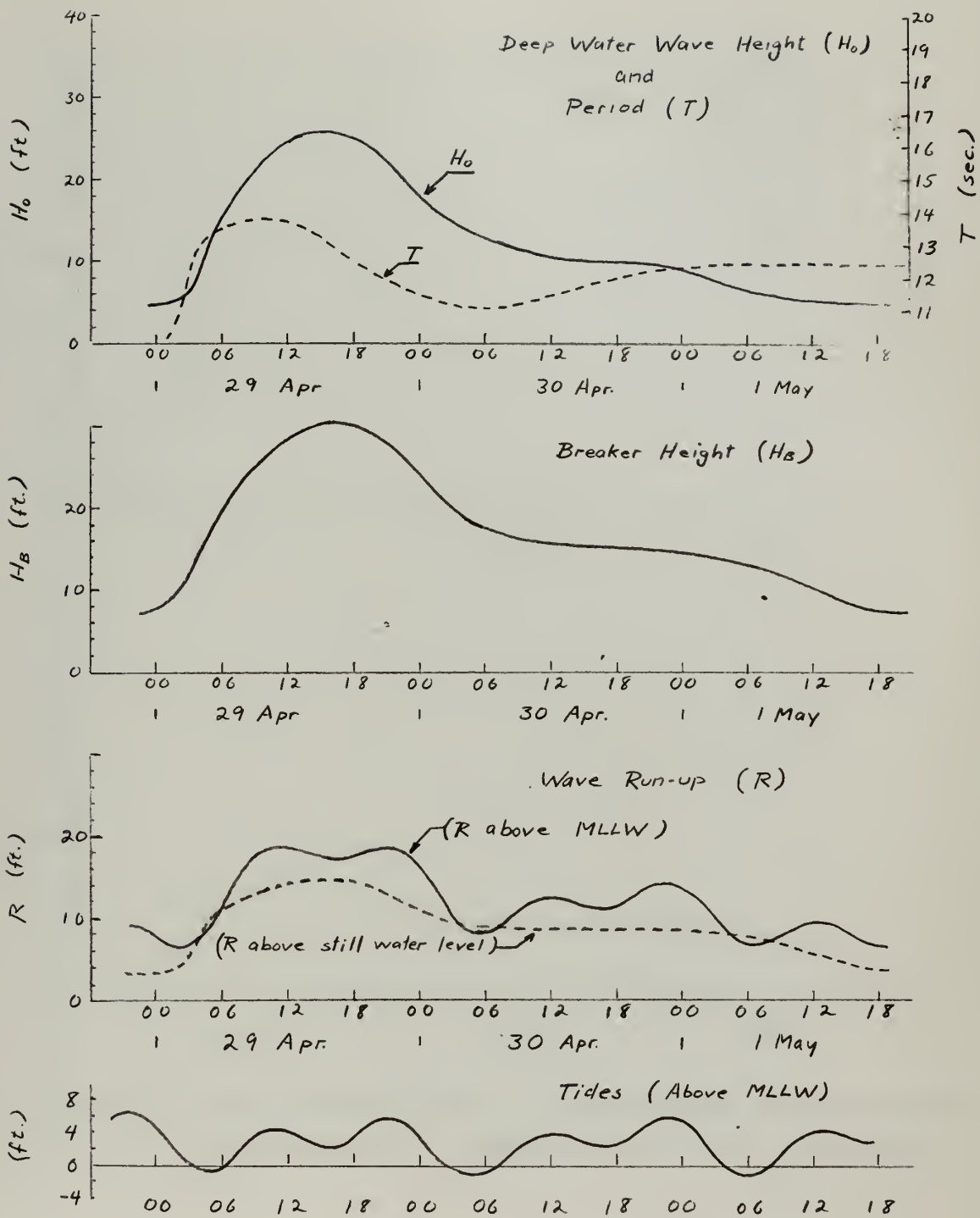


Fig. 7a. Storm of 29 April 1915. Wave height and period in deep water; breaker height and wave run-up in Monterey Harbor. Highest waves were reported the night of the 29th.

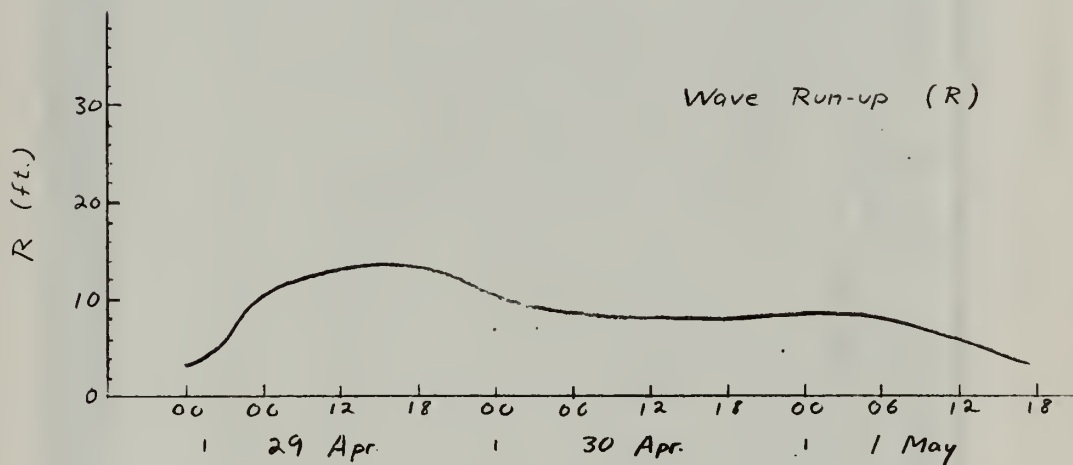
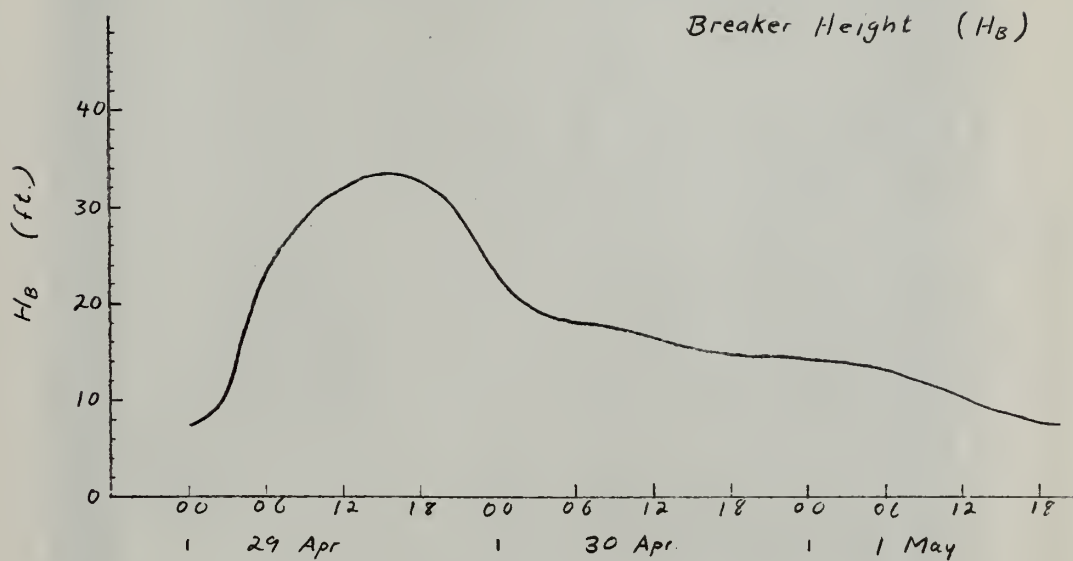


Fig. 7b. Storm of 29 April 1915. Breaker height and wave run-up near Moss Beach. Heights are above still-water level.



Fig. 8. Damage from the storm of 29 April 1915.



#### 4. Bay Wind Storms.

This section includes a descriptive account of each of the eight selected Bay Wind Storms with regard to damage inflicted, wind velocity, wind duration, and waves. From the descriptions given, a comparison of severity of damage and intensity of wind is made.

Actual wind observations at Monterey were available for only the most recent of the storms, February 1953, and are included in Appendix V. These winds were reported on the hourly Aviation Weather observations from the Monterey Airport and are considered to be reasonably representative although probably not as strong as winds over the water. The only other direct wind information available was the newspaper reports of maximum wind speeds for this storm and for the December 1943 and the February 1931 storms. No mention of the source of these reports was made. The assumption is made that these maximum reported winds were actually the maximum gusts rather than the steady wind. This assumption is based on what this writer has personally observed to be the general practice of the local newspapers. All other winds used in the analysis of these storms were deduced from surface weather maps, either 6 or 24 hours apart, by either plotted wind symbols in the vicinity of Monterey or by means of the isobaric gradient. The latter winds, particularly, cannot be considered too accurate since the weather maps used were designed to depict an overall synoptic situation rather than to specify local conditions over Monterey Bay.

A single significant deep-water wave height hindcast for the time of maximum wind speed, as determined according to the preceding paragraph, is also given for each storm in Monterey Harbor. Breaker height is computed as in the Open Ocean Storms for a beach of a composite slope

of 1:10 approximating the actual beach in Monterey Harbor. Refraction coefficients are not available for the directions of approach from northwest through north to northeast, so a single assumed value of 0.75 is used in computing the equivalent deep-water wave height. It should be remembered that the harbor has been partially protected by the break-water since 1934 and thus only a portion of the beach directly in line with the approach of the waves was actually exposed to breakers of the magnitude indicated. Tides are not considered since most of the damage was inflicted upon boats either floating or aground at whatever tide level existed at the time. Pier damage was generally the result of boats smashing into pilings, and this was also independent of the water level. Wave run-up is not considered because newspaper accounts indicate that damage was inflicted predominantly on boats in the harbor by a combination of wind and wave action. Erosive shoreline damage characteristic of high run-ups was significantly absent.

Following the descriptions of the individual storms, a summary of the important wind and wave characteristics of each is presented; from which their relative intensities are estimated on the basis of estimated maximum wind velocity, wave height, and damage inflicted.

Storm of 23 February 1953: The storm struck Monterey at about 0600 on the 23rd with considerable suddenness. Small-craft warnings had been displayed the previous day. Interpolating between the last wind observation taken the night of the 22nd and the first taken the morning of the 23rd (Appendix V), it appears that winds began to show the characteristic gustiness about 2100 on the 22nd and shifted to northerly within a few hours. According to the newspapers, the maximum winds were 53 knots at 0600 and this was the time that most of the damage occurred.

This wind was probably more in the nature of gusts than a steady wind since wind observations at 0525 and 0625 indicate steady winds of less than half the reported maximum.

Damage consisted of seven large fishing boats broken loose from their moorings and blown into one another and ashore with a loss estimated at \$500,000. With high winds and rough water the boats were driven high onto the beach. The four largest boats were all aground by 0630, three of these being in an area supposedly protected by the breakwater. The storm consisted of winds only; no precipitation or extensive cloudiness was involved. While winds at the Monterey Airport were reported as north-northwest to north, the storm was described as a north-east gale by the newspapers.

The maximum dimensions of the waves hindcasted at the Harbor at 0600, the time of peak winds, were a deep-water wave height of 8 feet, a period of 6.5 seconds, and a breaker height of 7 feet. The hindcast is based on the assumption that winds increased from a steady 15 knots at 2200 the previous night to a steady 35 knots at 0600. Unquestionably, damage was not due to waves alone but to the combined action of the wind and waves and breakers pounding the stranded boats.

Storm of 8-9 December 1943: At 2300 on the night of 8 December this storm, described by newspapers as a fierce northeast gale, struck Monterey Harbor. The storm arrived without warning, the published forecast being for fair weather. Within an hour the winds were reported as having reached a peak speed of 56 knots. No weather phenomena other than strong, dry, gusty winds were associated with the storm, which extended over all of west central California. Winds continued strong throughout the 9th although diminished considerably from the peak values.

A geostrophic-wind analysis of six-hourly surface weather charts shows a surface wind in Monterey Bay at 2330 on the 8th of 29 knots, and at 0430 on the 9th a surface wind of 52 knots. By the time of the 1030 map on the 9th, according to the geostrophic analysis, the wind was down to 29 knots again. Assuming the news reports to be correct, winds of at least 40 knots probably blew almost continuously from 2400 until at least 0430. The wind direction was northeast and accordingly had a very short fetch over Monterey Bay which yielded significant deep-water wave heights of 11 feet, with a period of 7 seconds. On the beach such wave conditions would have produced a breaker height of 9 feet. It is not difficult to visualize how such conditions can produce considerable damage in a small harbor.

In this instance the storm resulted in harbor damage totaling an estimated one million dollars. A total of some 40 boats was damaged or lost, including three large purse seiners. A small portion of the damage to the fishing boats is shown in Figs. 9a and 9b. In addition, many pilings on the municipal wharf were seriously weakened, planks were blown off of Fishermen's Wharf, and varying amounts of wind damage were inflicted upon privately owned beach property. It was said in accounts of the storm that even the above damage was light compared to what might have been expected with such a violent storm. However, as a result of the forecast for fair weather, nearly all the large boats were at sea and when reports of the storm reached them most returned to the shelter of Santa Cruz. Had a storm been forecasted, it is quite likely that most of the boats would have remained in Monterey Harbor where they normally can expect a safe anchorage.



Storm of 24-25 December 1942: This storm was apparently rather short in duration, with news reports describing conditions only as a night of north winds and high surf. Damage occurred in the early morning hours of the 25th with four purse-seiner type fishing boats, having a total value of \$115,000 to \$175,000, breaking or dragging their moorings and being driven aground. Two of the boats were salvaged with moderate damage, but the other two were total wrecks. In addition, a number of other boats were damaged by being knocked against one another at their moorings. Total damage to boats, which was the only type of damage reported, was estimated at about \$75,000 to \$80,000. No wind velocities at all were reported for the storm, but by obtaining surface winds from geostrophic winds (adjusted for stability and isobar curvature) using the Northern Hemisphere Historical Series surface map at 0830, a surface wind of 32 knots is indicated. These winds do not seem particularly strong; however, if they existed for at least 3.5 hours, waves of 8-foot significant height could have been generated. Associated with this height would be a period of 6.3 seconds, yielding a breaker height of 7 feet. The combination of wind and wave forces was apparently sufficient to cause the damage. In addition, with mean winds of 32 knots, it is reasonable to assume gusts of 45 knots or more probably occurred.

Storm of 20-21 November 1931: The wind in this storm began the night of the 20th and increased in intensity until winds of 44 knots were reported in the early afternoon of the 21st. Damage consisted of five medium-sized boats wrecked on the beach, in addition to many smaller launches and skiffs. No dollar estimate of the damage was given. Surface winds obtained from geostrophic winds were about 26 knots on the



0430 map of 21 November and about 30 knots at 1430. Assuming a steady wind of 30 knots beginning at 0430, waves at 1400 had a significant height of 8 feet with a 6.2-second period, producing breakers of about 7 feet.

Storm of 20 February 1931: Strong north winds reported to be of gale intensity struck the Harbor in the early morning of the 20th. Heavy surf was reported in the vicinity of the Custom House, and five fishing boats were driven ashore and damaged to varying degrees for a total loss of \$6,000.

Assuming that the winds were indeed of gale force, a wind speed of at least 40 knots is indicated for the storm. Winds determined from the 0430 surface map indicate only 16 knots in Monterey Bay; however, a plotted wind from a ship just offshore shows 35 to 40 knots. This situation, in addition to the fact that the map time is somewhat later than the apparent time of peak observed winds, led the writer to believe that winds in the area were at least 35 to 40 knots. Assuming a steady increase in wind to 37 knots, waves of about 10 feet significant height and 6.7-second period were probably present and produced surf greater than 8 feet in height.

Storm of 30 November - 1 December 1923: Winds in this storm, described as a northeast gale, began increasing in force the night of 30 November. At 0230 on the morning of the 1st, what was termed "a particularly strong wind" started tearing small craft from their moorings. The duration of the strong winds was not reported. In all, some 15 fishing boats of varying sizes were driven ashore. Damage from the storm totaled \$20,000.

Surface winds over Monterey Bay were determined from geostrophic

winds at 0430 on the 1st as 24 knots. This seems rather light, however, as San Francisco reported winds of 34 to 40 knots at that time; and a ship about 20 miles offshore reported 28 to 33 knots. Both stations were in an area where isobaric spacing was the same as at Monterey, suggesting that the geostrophic winds obtained from the map are too light. For hindcasting purposes, the writer assumed that a wind speed of at least 32 knots existed at 0430 (and probably higher at 0230 when the storm hit the hardest); this would have produced 6.3-second waves of 8-foot height as was the case in the 1942 storm described above. Such deep-water waves would yield 7-foot breakers.

Storm of 26-27 November 1919: The storm of Thanksgiving night, 1919 is perhaps the best-remembered storm by old-timers of the Monterey area. A total of 93 launches and lighters was wrecked. While the total worth of the damage was less than in the 1943 storm, the damage was more extensive and economically more of a disaster at the time. This was primarily because the winds managed to wreck more than half of the fishing fleet, thus eliminating the means of livelihood for a great many people. In this sense it is difficult to evaluate the damage quantitatively. The fact that the storm came without warning and occurred on a holiday when most persons were not aboard their boats undoubtedly contributed to the amount of damage. In addition to boats, a wharf was severely damaged by the impacts of loose boats.

Winds were reported to have been strong from the southwest during the afternoon and evening of the 26th, and then to have veered to the north and rapidly increased in strength that night. The time of the windshift was not given, but from news accounts it apparently was sometime before midnight. The 0430 map on the 27th indicated a north wind of 30 knots from a geostrophic analysis, and a ship report about 100 miles offshore

showed winds of Beaufort Force 9, indicating at least 41 knots. From this information it is probable that a surface wind existed having a peak speed near 50 knots and a sustained speed of 40 knots for about two hours. This would have produced 6-second waves of a significant height of 8 feet, duration limited, and approximately 7-foot breakers. Without the protection of the breakwater it appears that these wind and wave conditions would have been more than sufficient to wreak havoc among the fishing fleet.

Storm of 4 October 1912: This storm was described as a strong northwest wind accompanied by a heavy swell. Surf was described as dashing over the boardwalk near the railroad depot in Monterey and up against the Wells Fargo Fish House. The worst of the storm occurred about 1900 on the 4th. Damage included washing away of a small-boat wharf, and a number of small craft driven ashore and damaged. No estimate of damages was given.

While waves seem to have been a little more noteworthy than is usual for this type of storm, it is more than likely that they were short-period waves generated mostly within Monterey Bay since no important fetch areas existed in the open ocean that would produce swell arriving about the time of the storm. However, the wind was somewhat more westerly than is usual for this type of storm; and it may be that the fetch area extended beyond Monterey Bay to the northwest. This would have resulted in larger waves in the vicinity of the Harbor.

It was difficult to deduce surface winds from the geostrophic winds in this case, since peak winds apparently occurred at least ten hours before the nearest map time. At 0430 on the 4th surface winds were about 31 knots. From apparent movement of the surface pressure pattern, a tighter pressure gradient may have existed between maps on the surface

at the time of the storm. Winds probably were near 40 knots peak value. It may also be assumed that at least a 30-knot wind blew steadily for at least three and a half hours near the time of the storm so that 6.2-second, 8-foot waves were generated. These waves would produce breakers of approximately 7 feet.

Summary of Wind and Wave Conditions Accompanying Bay Wind Storms:

Table 2 summarizes maximum values of winds and waves and the damage at Monterey Harbor for each of the eight storms.

Wind values given are the writer's own evaluation, based upon the factors considered in the discussion of each individual storm. In general, it is considered that gusts were approximately 15 knots in excess of the maximum steady wind speeds. Information was insufficient to be able to determine the duration of strong winds; hence, this factor is not considered. As pointed out earlier, winds need blow no more than 3.5 hours before the duration time ceases to be the limiting factor in wave generation. However, the author believes that if good wind data were available, it is quite likely that a rough relationship between amount of damage and duration of winds in excess of a certain speed could probably be found. On the other hand, the surprise element is apparently quite an important factor in the amount of damage; and this, of course, requires a short duration, at least before the time of maximum damage.

It is difficult to say whether a given wind direction is associated with the most severe damage in the light of such sketchy information. However, the only storm reported by the papers as having northwest winds seems to have been less intense from the standpoint of damage than most of the other storms, even though the wind speed was as high as in other more severe storms. On the other hand, northeast winds were associated

	<u>Jan 1953</u>	<u>Dec 1943</u>	<u>Dec 1942</u>	<u>Nov 1931</u>	<u>Feb 1931</u>	<u>Dec 1923</u>	<u>Nov 1919</u>	<u>Oct 1912</u>
Maximum Steady Wind (kts)	35	40	32	30	40	32	40	30
Maximum Wind Gust (kts)	53	56	45	44	55	45	55	45
Max H <sub>O</sub> (ft.)	8	11	8	8	10	8	8	8
Max H <sub>B</sub> (ft.)	7	9	7	7	8	7	7	7
T of Max H <sub>O</sub>	6.5	7.0	6.3	6.2	6.7	6.3	6.0	6.2
Damage (actual)	\$500,000	\$1,000,000	\$80,000	\$1,000	\$6,000	\$20,000	\$150,000	\$1,000
Damage (1960 base)	\$590,000	\$1,600,000	\$134,000	\$2,600	\$15,000	\$28,000	\$185,000	\$1,600
Direction of Approach	NE	NE	N	N	N	NE	N	NW

Table 2. Summary of Characteristics of Important Bay Wind Storms.



with the two storms that resulted in the most severe damage.

Wave heights given in Table 2 are the maximum significant heights hindcasted for each storm. Since storm durations were relatively short and information on the wind field very poor, no attempt was made to hindcast waves for the whole storm. For this reason hindcast worksheets are not included for the Bay Wind Storms.

Amounts of damage in the Bay Wind Storms, as shown in the table, are adjusted to the 1960 base [14] to facilitate comparison.

The 1943 storm was obviously the most severe on the basis of the amount of damage inflicted, being nearly three times as great as in the February 1953 storm. In terms of the wind force, however, it does not seem that much more severe. The author here can offer only the factor of the suddenness of the storm as the cause for so much more damage in the earlier storm. The November 1919 storm is probably the third worst storm in the 50-year period. As noted previously, the damage was difficult to survey accurately, since, besides physical damage, the local economy was seriously affected. Also, the equipment used in those days (boats, nets, machinery) represented a relatively smaller investment per boat than in the case of vessels lost in the more recent storms.

While wave forces in the Harbor unquestionably have contributed significantly to damage in the Bay Wind Storms, the author strongly feels that wind forces, rather than wave action, played the primary role in causing the described damage.



Fig. 9a. Damage from the storm of December 1943.

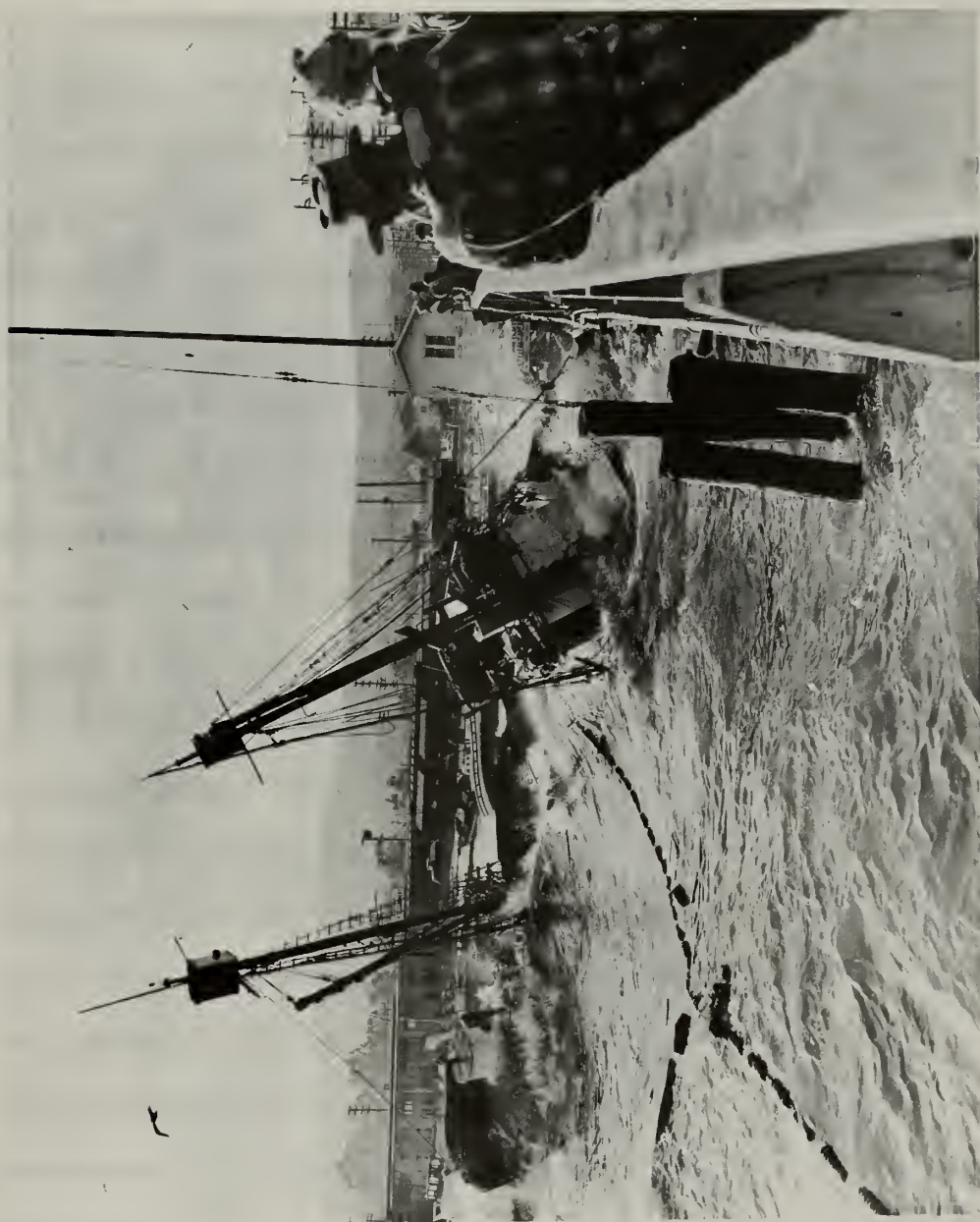


Fig. 9b. Damage from the storm of December 1943.



## 5. Synoptic Situations Associated with Open Ocean Storms.

In this section, the synoptic situations associated with Open Ocean Storms at Monterey are described. As stated earlier, study of the synoptic situations was made with the hope of finding aids to forecasting these storms. In order to facilitate finding such aids, the storms were classified using a weather-typing system developed by California Institute of Technology [9] and Elliot [10] .

Of interest in this paper are zones extending from the 180th meridian eastward to 135W and from 135W to 90W. In Elliot's terminology these zones are the Pacific Zone, or Zone 2, and the North American Zone, or Zone 3, respectively. These zones were set up by Elliot based upon an average speed of movement of a cyclone of about 15 degrees of longitude per day and an average length of time between passages of members of a cyclone family of three days. The two general classes of weather types are zonal and meridional, and these are broken down into more individual types according to the surface synoptic weather patterns as determined by isobaric analyses and according to trajectories of high and low pressure systems. Also, in some types the upper-air patterns are important in determining the weather type. One of the most important factors in determining the basic type is the position of the eastern lobe of the Pacific anticyclone. The two most common weather types found to be associated with the Open Ocean Storms are shown schematically in Figs. 16 and 17 at the end of this section.

At this writing, weather maps suitable for reproduction in this paper were not yet available for the 1960 storm. As a result, only a sketch of the situation is included. For the other storms, the 24-hourly Northern Hemisphere Series is in part reproduced here in order to show

the nature of the storms. Map times are all stated in Greenwich Mean Time and are at 1200Z or 1230Z daily. All maps are presented at the end of this section in Figs. 10 through 15. If not otherwise indicated, the location of Monterey is shown by a star (★) in each map.

For each storm, whenever applicable, two values have been computed: (1) the speed of the primary cyclone and (2) the latitude at which the primary cyclone enters Zone 3. The primary cyclone is that cyclone with which the generating area producing the highest deep-water waves is associated. Its speed is calculated from the time of the earliest map on which the storm can be discerned to the time of the last map on which there is a component of eastward motion or on which the storm has moved inland. A description of the individual storms follows.

Storm of 8-9 February 1960: Fig. 10 is a sketch showing the storm track from 8 to 10 February. From the 4th through the 7th the picture seemed fairly static with low pressure over all of the Gulf of Alaska. A front extended from this region westward across the Pacific, and on this front existed a series of frontal waves and cyclones. The cyclone producing the waves at Monterey was first noticed on the 0000Z map on the 7th approximately 1800 nautical miles from Monterey. As it moved eastward it continued to deepen, and winds behind the cold front increased. The 0000Z map of the 9th shows the storm center at its minimum pressure of 964 mbs and the fetch still somewhat offshore; the storm center reached the coastline by the 0600Z map, as shown by the position of the cold front in Fig. 10. The low center subsequently drifted northward, slowly filled, and the winds decreased.

Elliot's CIT Weather Types would class the weather pattern as a  $B_S$  through the 7th and then  $E_L$  for the remainder of the storm and for



several days following. Winds at Monterey are shown in Appendix V for the day of the storm. The storm moved at a rate of 18.4 degrees of longitude per day and entered North American Zone 3 at 45N.

Storm of 26 October 1950: Figs. 11a through 11e depict the weather patterns from 24 through 28 October, respectively. On 24 October a 1000-mb low, which separated from the parent cyclone just east of the Kamchatka Peninsula, is located at 48N 179E in the first figure. This low center moved westward with an associated frontal system and appeared from the closely packed isobars to be a strong generating area. Winds in this area were in excess of 40 knots. By the 26th, with continuing winds, the low deepened to 980 mbs and the center was located about 400 miles off the Oregon coast. Fig. 11d depicts the pattern on the 27th at 0430 PST, the cyclone having moved inland leaving an area of southwest winds along the coast as far south as San Francisco. From an analysis of the maps for the storm waves it was the time that this wind area first reached the coast that the largest waves appeared at Monterey. The time was determined in this case by interpolation between maps.

Both the maps of the 26th and 27th are typical examples of the basic weather pattern for this type of storm. The Pacific anticyclone was situated somewhat south of its normal position for the time of year, and a series of waves appeared along a quasi-stationary front extending from the Pacific Coast of the United States westward to about 160E. To the north of this front lay a series of quasi-stationary cyclones. The winds associated with the low-pressure systems along the front produced the waves.

The sequence aloft for this storm was fairly simple. Initially a cut-off low existed off the California coast. By the 25th it had filled to

a trough; the main stream had shifted somewhat south and helped to steer the storm centers onto the California-Oregon coast. As the trough filled, the upper flow became extremely zonal and a very long fetch was evident on the surface (Fig. 11b).

According to the CIT Weather Types and to Elliot, this pattern would be classed as a North American  $E_L$  type starting on the 23rd. Prior to that date the pattern was a  $B_{N-c}$  type.

Winds observed at Monterey are given in Appendix V. The reader will notice that while strong winds were reported at Monterey commencing at 1025 on 26 October, the waves did not build up until about 1500, more than four hours later. This phenomenon was probably the result of the fetch moving faster than the waves being generated, so that several hours were needed for the maximum wave energy to arrive. The average speed of the storm as it moved across the Pacific was approximately seven degrees of longitude per day. It entered North American Zone 3 at latitude 43N.

Storm of 23-29 December 1931: The maps depicting the weather situation are shown in Figs. 12a through 12g for 21 through 27 December, respectively. There were several wind areas generating large waves associated with this storm, but only one that approached close enough to the coast so that the swell arrived without experiencing excessive decay. While no upper-air charts are available, the surface map exhibits quite well the zonal characteristics of the flow pattern of 1200Z, 21 December. At that time a quasi-stationary low was located over northwest Alaska and the Bering Straits. A front curving through the Gulf of Alaska and trailing westward across the Pacific initially extended southeastward from this low center, and an open wave traveled along the front. This front and an old occlusion about 1200 miles to the southeast had wind areas behind them

generating large waves which, although reaching Monterey, were quite reduced in height. On the 22nd the same general situation existed with the open wave along the front advanced to 160W. By the 23rd this disturbance had moved into the trough of the original quasi-stationary low, had become an occluded cyclone, and had deepened to 975 mbs. The wind area that can be seen on the map produced the forerunners of the storm waves described in Section 3. On 24 December the storm had moved inland into western Canada, but had left an area of high winds behind it at sea. On this same map one may observe another wave on the front at about 171E (first observed on the map of the 23rd at 155E). This rapidly moving wave occluded by the 25th and deepened to 990 mbs. The succeeding map shows this storm having a central pressure of 965 mbs and being located just off the coast of British Columbia and beginning to stagnate. The winds to the south of the low-pressure center were those producing the largest waves at Monterey. The map of the 27th shows a very large area of high winds as well as a new storm located at 49N, 174E moving westward along the front. This storm also developed but never reached close enough to the North American coast to cause trouble.

The CIT Weather Type for the entire period is classified as E<sub>L</sub>. The northwest winds reported by the newspapers the night of the 26th to 27th were apparently the result of local influences, such as topography, as the maps would indicate that south and southwest winds prevailed. The speed of the primary cyclone as it moved across the Pacific averaged 18.2 degrees of longitude per day. The storm center crossed into North American Zone 3 in latitude 47.5N.

Storm of 11-15 February 1926: The synoptic patterns associated with this storm are shown in Figs. 13a through 13i depicting the 1200Z maps

from the 7th through the 15th, respectively. On the 7th of February a ridge of high pressure existed over the western part of the United States and a quasi-stationary low was in the vicinity of the Gulf of Alaska. From this low a front paralleled the coast of southern Alaska then swept back across the Pacific to the west. Along this front were situated several low-pressure areas. On 7 February the storm, which finally reached Monterey on the 12th with its attendant high waves, was an open wave on the front located about 158E and not visible in Fig. 13a. The high-pressure area began its eastward movement on the 10th, permitting the storm center to move in close to the California coast on the 11th. At the same time the quasi-stationary low that had been over the eastern end of the Aleutian chain had moved westward and the two storm centers merged. This was the situation as of 11 February, and as may be observed on that map, a large area of strong westerly surface winds followed the storm front. On the 12th the southern half of the storm had reached the coast and strong winds had brought the fetch area into a zero decay-distance situation. For the remainder of the storm period the coast continued to be hit by more storms, but after the 12th no areas of strong winds can be observed on the maps.

By Elliot's CIT Weather Types, a  $B_S$  type existed until the 10th of February, after which an  $E_L$  pattern was established. On the 14th the  $E_L$  type became  $E_M$  and then  $E_H$  on the 17th. The primary cyclone entered Zone 3 at 38N and its average speed was 10 degrees longitude per day.

Storm of 27 January 1916: Figs. 14a through 14f depict the synoptic situation at 1200Z on 23 through 28 January 1916. The storm that was centered over Vancouver Island on the 23rd had moved rapidly across the Pacific during the previous few days, but the map of the 23rd gives the



first indication of any appreciable generating area. The fetch, however, was too far north and too close inshore to produce noticeable waves at Monterey. However, on the next map a new storm may be seen off British Columbia, and this maintained the heavy seas in the area of the earlier storm of the 23rd which had since moved inland. It also appears from a study of this map that further eastward movement of cyclones from the Pacific was blocked by a strengthening ridge. By the 27th the new storm had moved southward and was centered over San Francisco. In this position the reader may observe that the high winds circulating around the storm formed a fetch oriented northwest-southeast which directed large waves into Monterey Bay. The southwest winds mentioned in Section 4 were probably occurring very close inshore, even after the frontal passage on the 27th.

The CIT Weather Type for this pattern was  $E_H$  until the 23rd. The map of the 24th and those later indicate an A type until sometime after the storm occurred at Monterey. Cyclogenesis took place east of 135W and therefore the usual measuring parameters were not used.

Storm of 29-30 April 1915: The weather patterns associated with this storm are shown in Figs. 15a through 15d. There seems to be little significance to the pattern prior to the day of the storm except that the storm which reached Monterey may be followed along its track. It was not associated with particularly strong winds, however. The low appears to have been quasi-stationary over Alaska until the 28th, when it started a southeastward movement. On the map of the 29th very strong northwest winds appear on the coast as far south as Monterey.

Weather typing from five days prior to the storm showed a type B through the 28th, changing to type A as the ridge strengthened and the



flow became meridional. This type continued for several days after the storm. Since movement of the primary cyclone across the Pacific did not occur, the speed of the storm center and its latitude cannot be compared with the other storms. It is noted, however, that the trajectory of this storm was displaced considerably eastward of the January 1916 storm. This difference allowed the strong wind area to reach Monterey from a more northerly direction in the 1915 case.

Discussion: It appears from a study of the preceding individual synoptic situations that there are two basic requirements for an Open Ocean Storm to reach Monterey. First, the circulation pattern must be such as to form a wave-generating area over the open ocean and it must exist for a long enough time to permit the waves to build up. Secondly, the fetch must reach a position relatively close to the California coast for the waves to be unusually large at Monterey. While apparently not an absolute requirement, the author feels that it is also noteworthy that five of the six fetches producing significant waves were associated with both an eastward-moving cyclone and a quasi-stationary cyclone located approximately off the British Columbia coast. The storm of January 1916 was the only exception.

Table 3 summarizes the key information obtained for each of the storms. Storm track, described by the latitude of entry into Zone 3, and storm speed are not given for the A types since all significant activity and wave generation took place east of 135W.

Some significance probably should be attached to the fact that four of the six Open Ocean Storms may be typed as  $E_L$  at the time they reached Monterey. However, Holland and Mills [16] in their weather-typing system described the  $E_L$  type over the Pacific in Zone 2 as probably the

	<u>Feb 1960</u>	<u>Oct 1950</u>	<u>Dec 1931</u>	<u>Feb 1926</u>	<u>Jan 1916</u>	<u>Apr 1915</u>
Elliot CIT Weather Type	E <sub>L</sub>	E <sub>L</sub>	E <sub>L</sub>	E <sub>L</sub>	A	A
Storm Track <sup>1</sup>	45N	43N	47.5N	38N	NA <sup>2</sup>	NA
Storm Speed (Deg. Long/Day)	18.4	7.0	18.2	10.0	NA	NA
Central Pressure (mb)	964	980	965	995	995	995

<sup>1</sup> Storm Track is given as the latitude in which the storm entered Zone 3.

<sup>2</sup> NA means not applicable.

Table 3. Summary of Synoptic Conditions for Open Ocean Storms.

most common of all types, at least in the winter months; and, according to Elliot [10] the Pacific Zone-weather type is most likely followed by the same North American Zone-weather type. Thus a predominance of  $E_L$ -weather types should be expected.

It is noteworthy that the tracks of these four storms lay somewhat south of the composite track of  $E_L$ -type cyclones. This composite track together with the tracks of the individual storms is depicted in Fig. 16. Note that the composite track enters Zone 3 at about 51N, whereas the four individual storms enter Zone 3 between latitudes 38N and 47.5N, with an average of about 43.4N. As stated previously, Elliot's weather typing is based on a storm speed of 15 degrees of longitude per day, and this should be considered the speed of a cyclone along the composite track. The speed of the 1960 and 1931 storms exceeded this value, whereas the other two were somewhat slower than the average.

The April 1915 and January 1916 storms, both of weather-type A, are more difficult to compare with the composite shown in Fig. 17, as neither storm fits the typical pattern particularly well. As seen by comparing their tracks with the composite, one storm was north and the other south of it and neither was radically different. There seems to be little to distinguish these storms from those that would be described as typical of the type.

In summary, destructive storms of the Open Ocean variety have been produced most typically by the  $E_L$  type of synoptic situation. This is true especially when one considers that the 1960 and 1950 storms, the two with the most remarkably large waves, according to the news accounts and wave hindcasts, were both classic examples of this type. The writer can draw no conclusions regarding the type A storms other than the fact that they also have produced important storms.

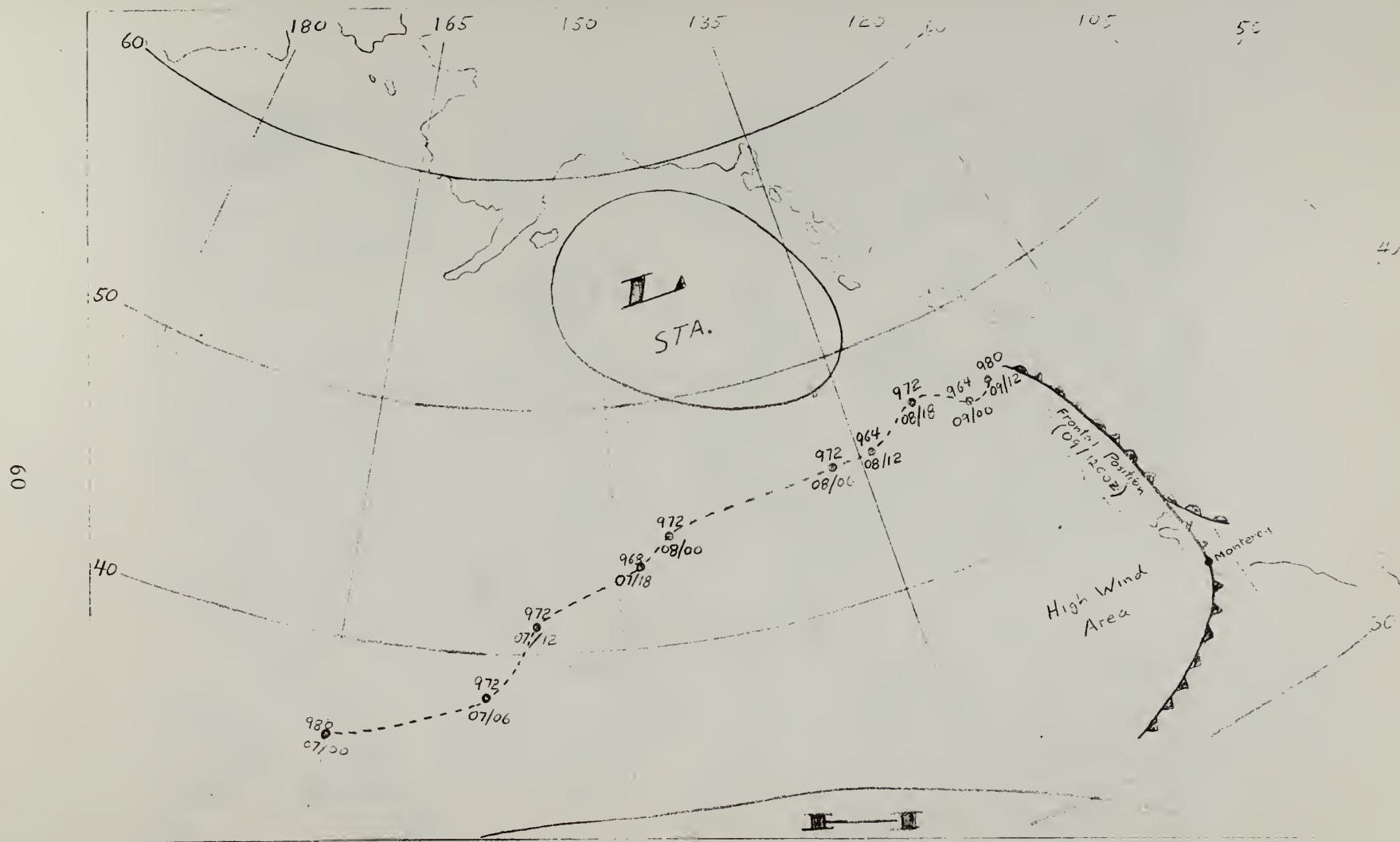


Fig. 10. Schematic surface weather map showing track and central pressures of February 1960 storm. High and low are composite of positions for entire sequence from 07/0000Z to 09/1200Z.



24  
F. 12. a

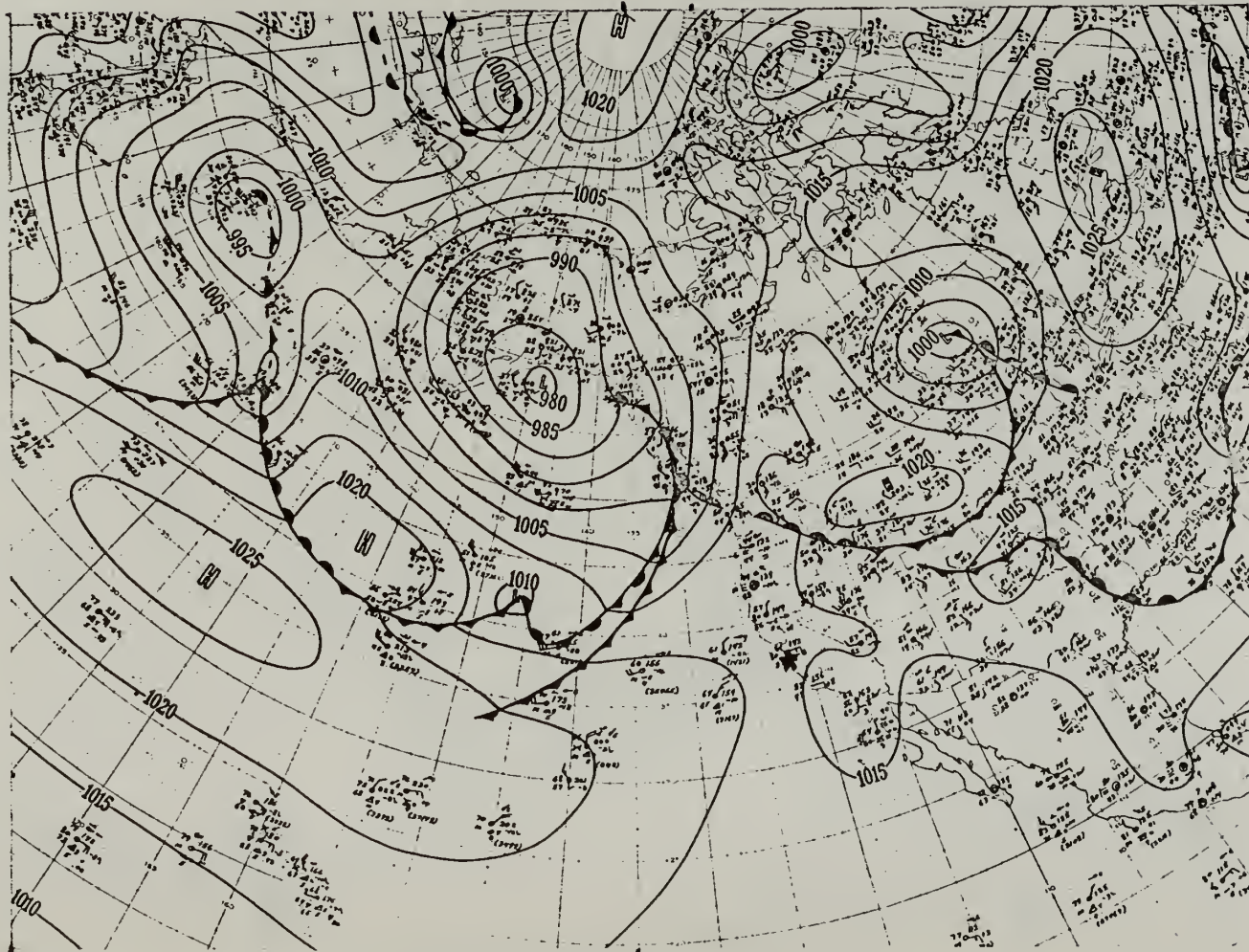


Fig. 11a. Surface Weather Map 1230Z 24 October 1950.



2 = 001

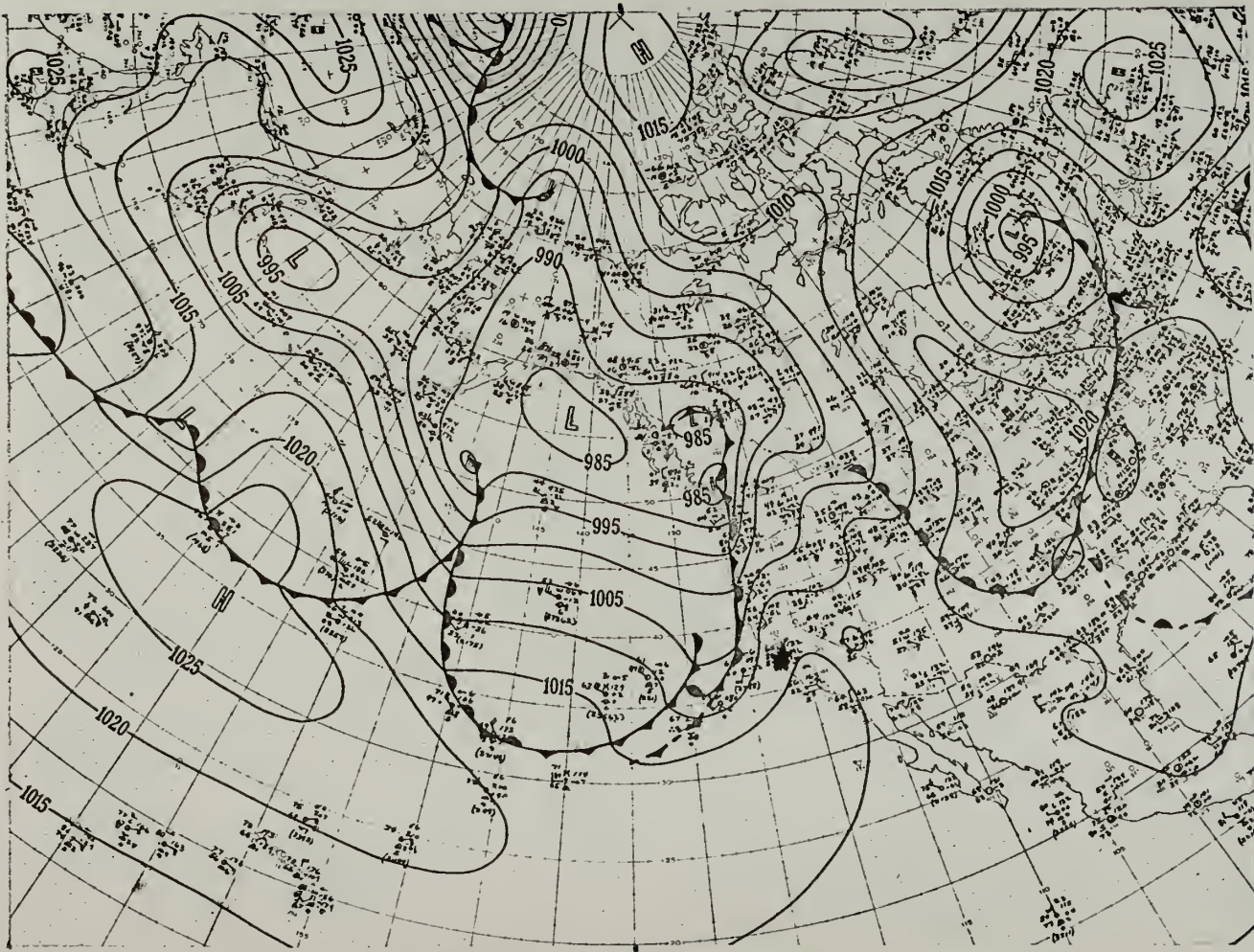


Fig. 11b. Surface Weather Map 1230Z 25 October 1950.

26 Oct

Fig. 11c

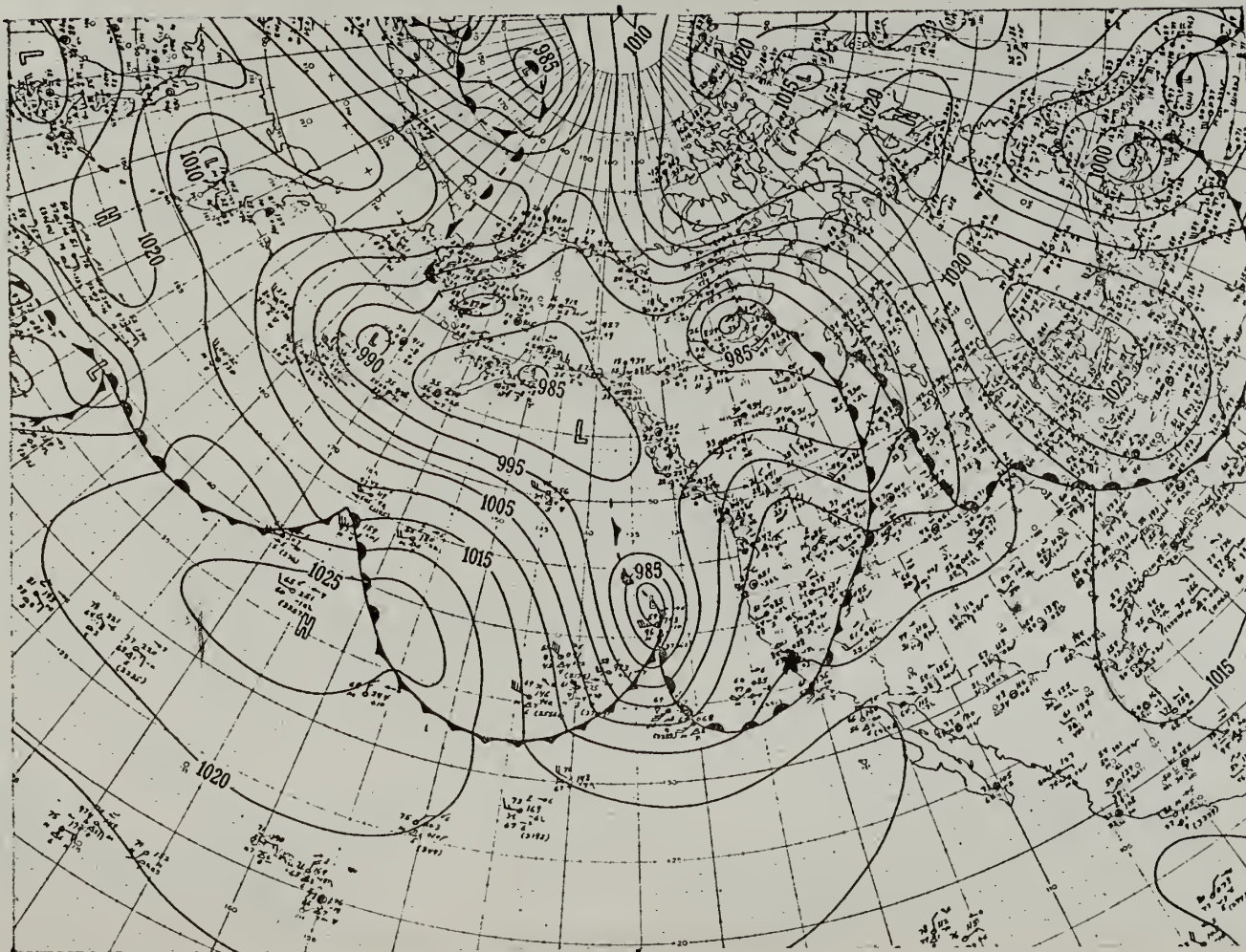


Fig. 11c. Surface Weather Map 1230Z 26 October 1950.



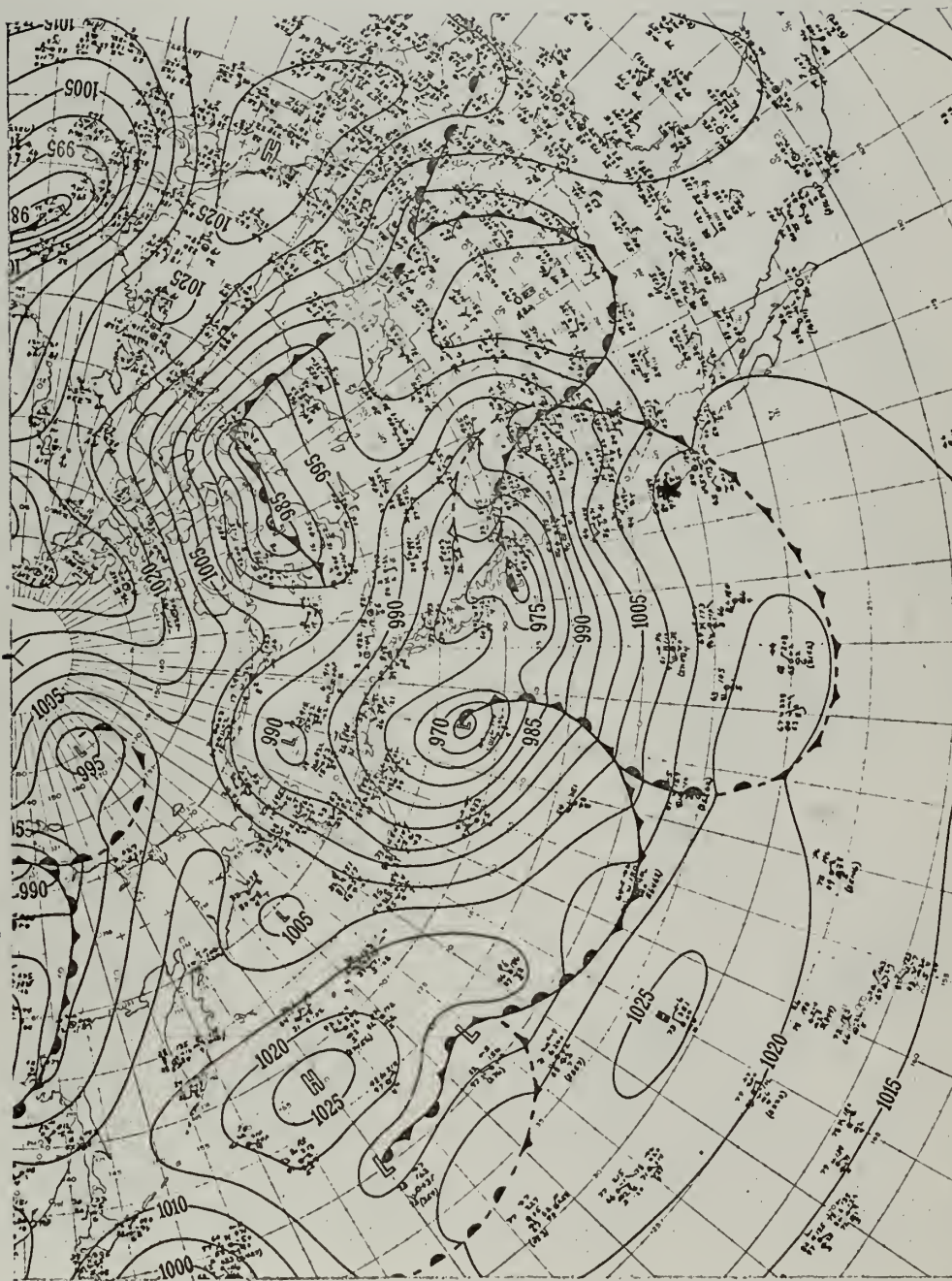


Fig. 11d. Surface Weather Map 1230Z 27 October 1950.

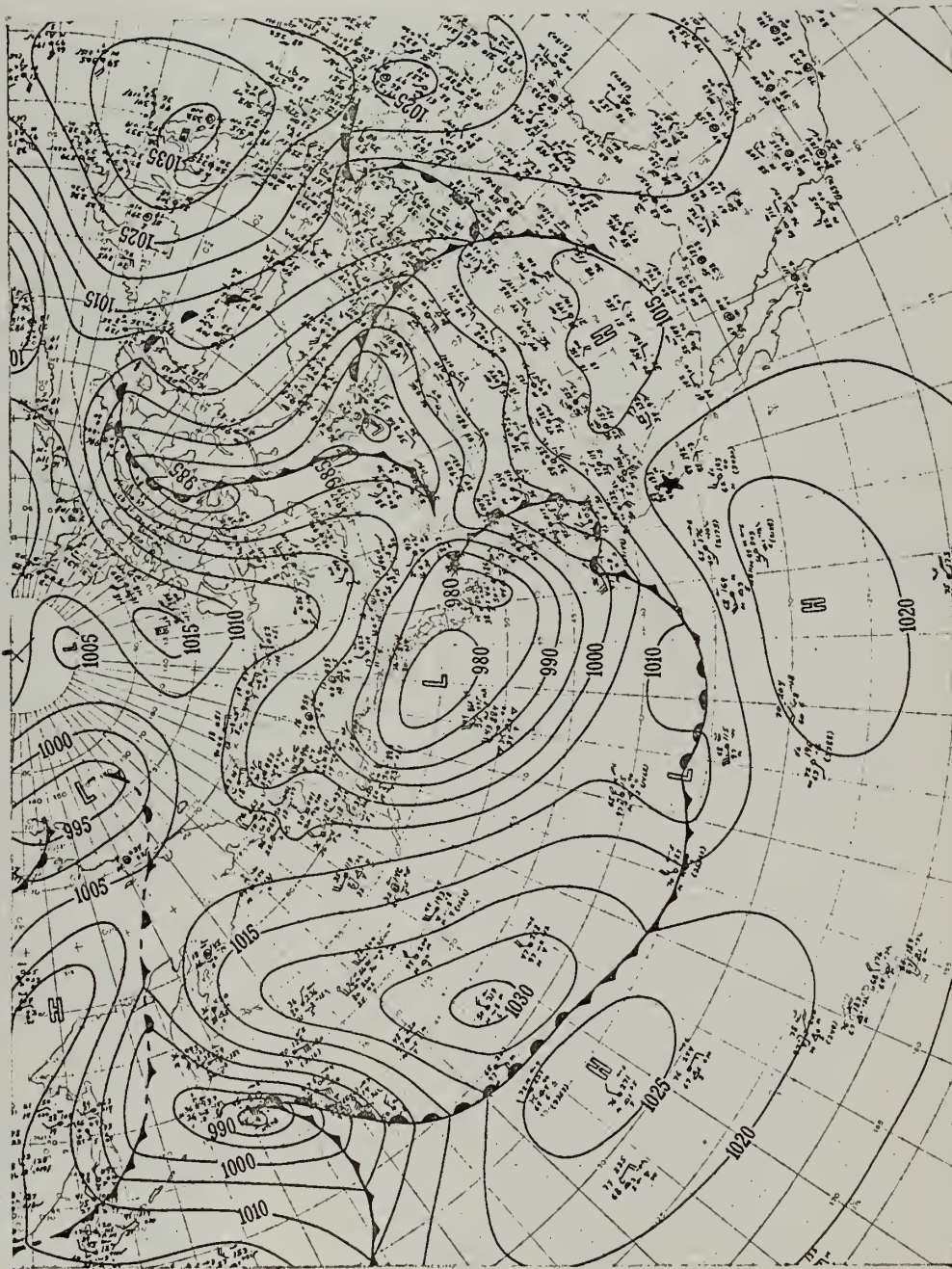


Fig. 11e. Surface Weather Map 1230Z 28 October 1950.





Fig. 12a. Surface Weather Map 1200Z 21 December 1931.



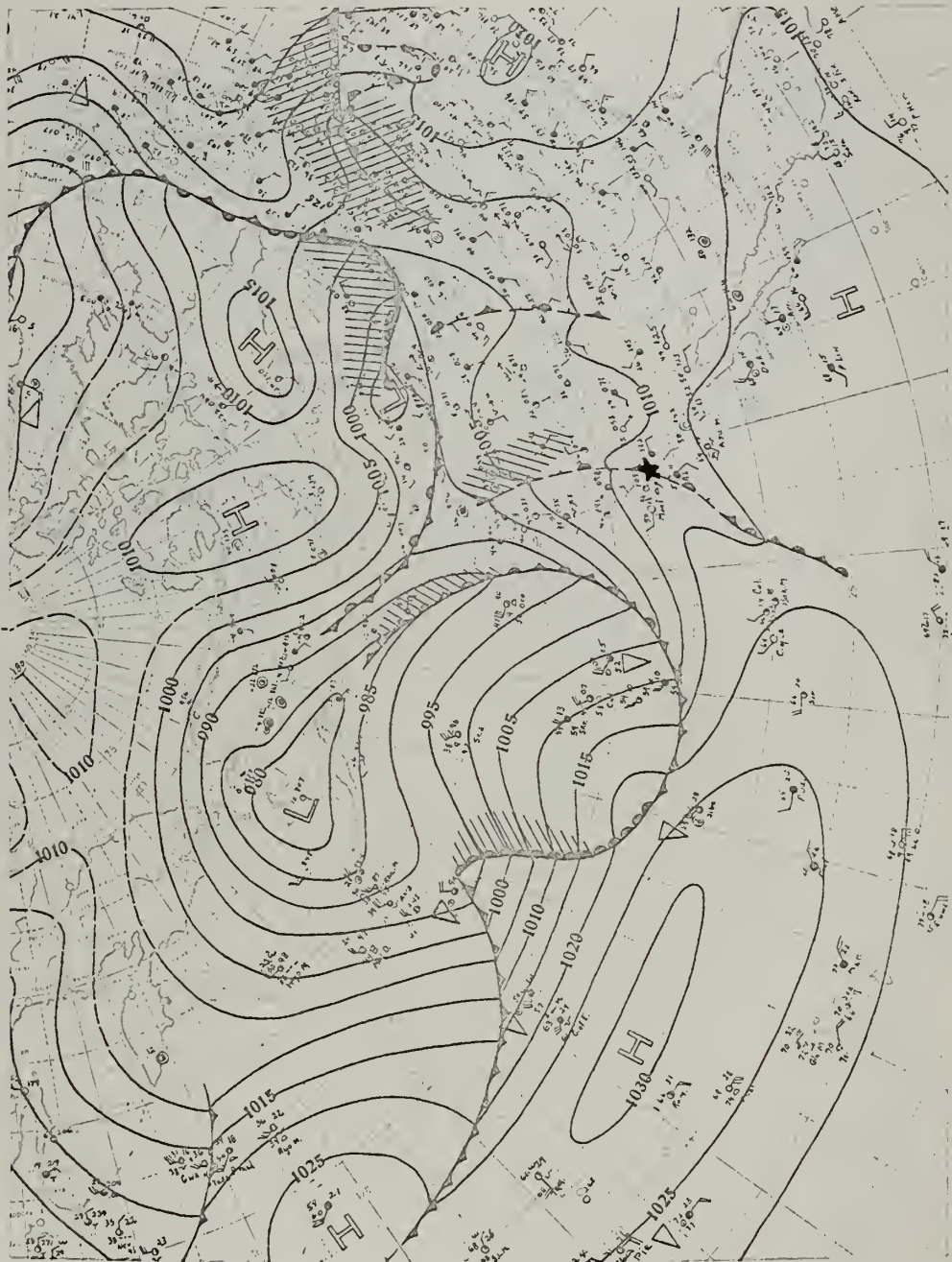


Fig. 12b. Surface Weather Map 1200Z 22 December 1931.

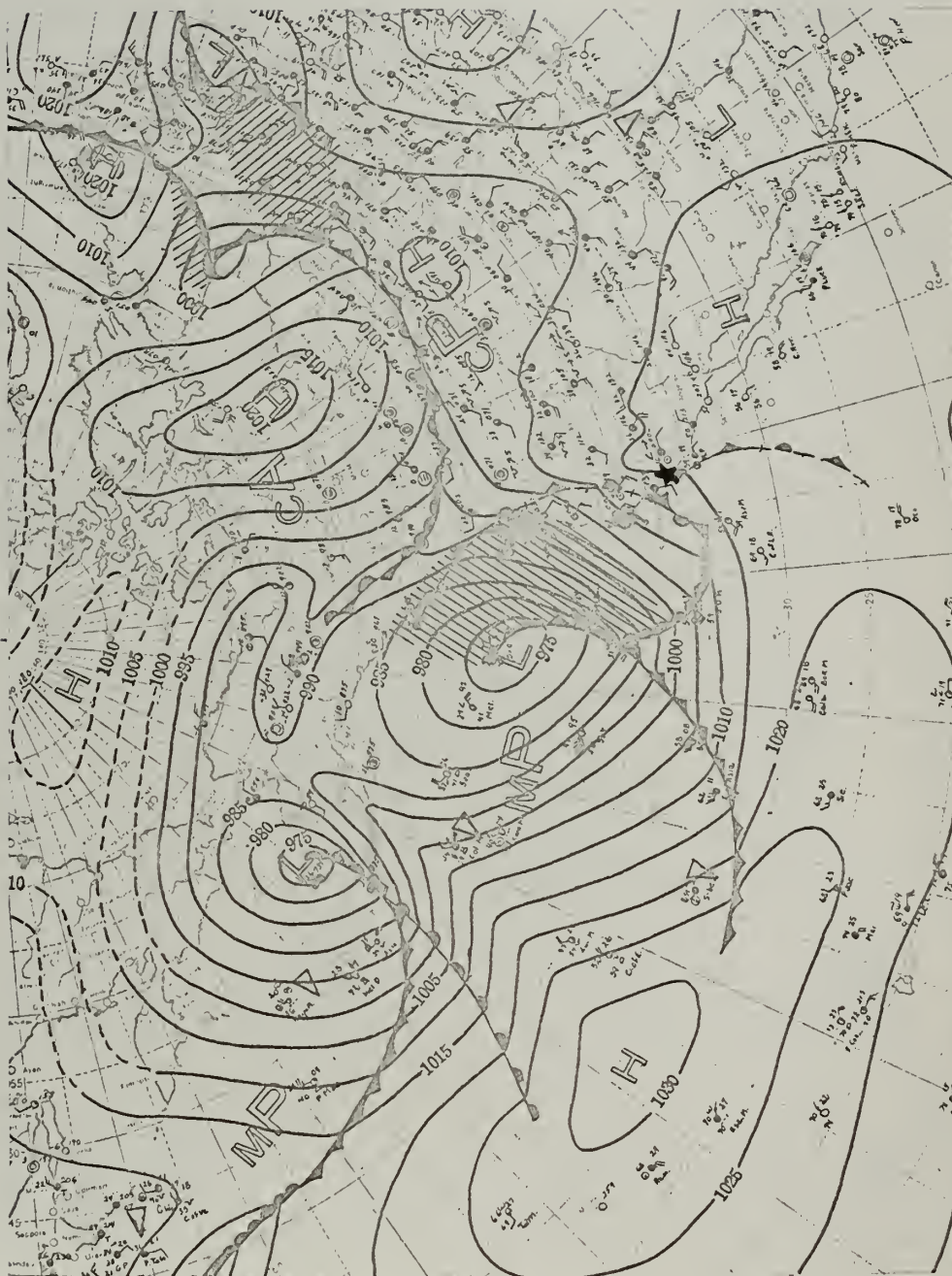


Fig. 12c. Surface Weather Map 1200Z 23 December 1931.



Fig. 12d. Surface Weather Map 1200Z 24 December 1931.



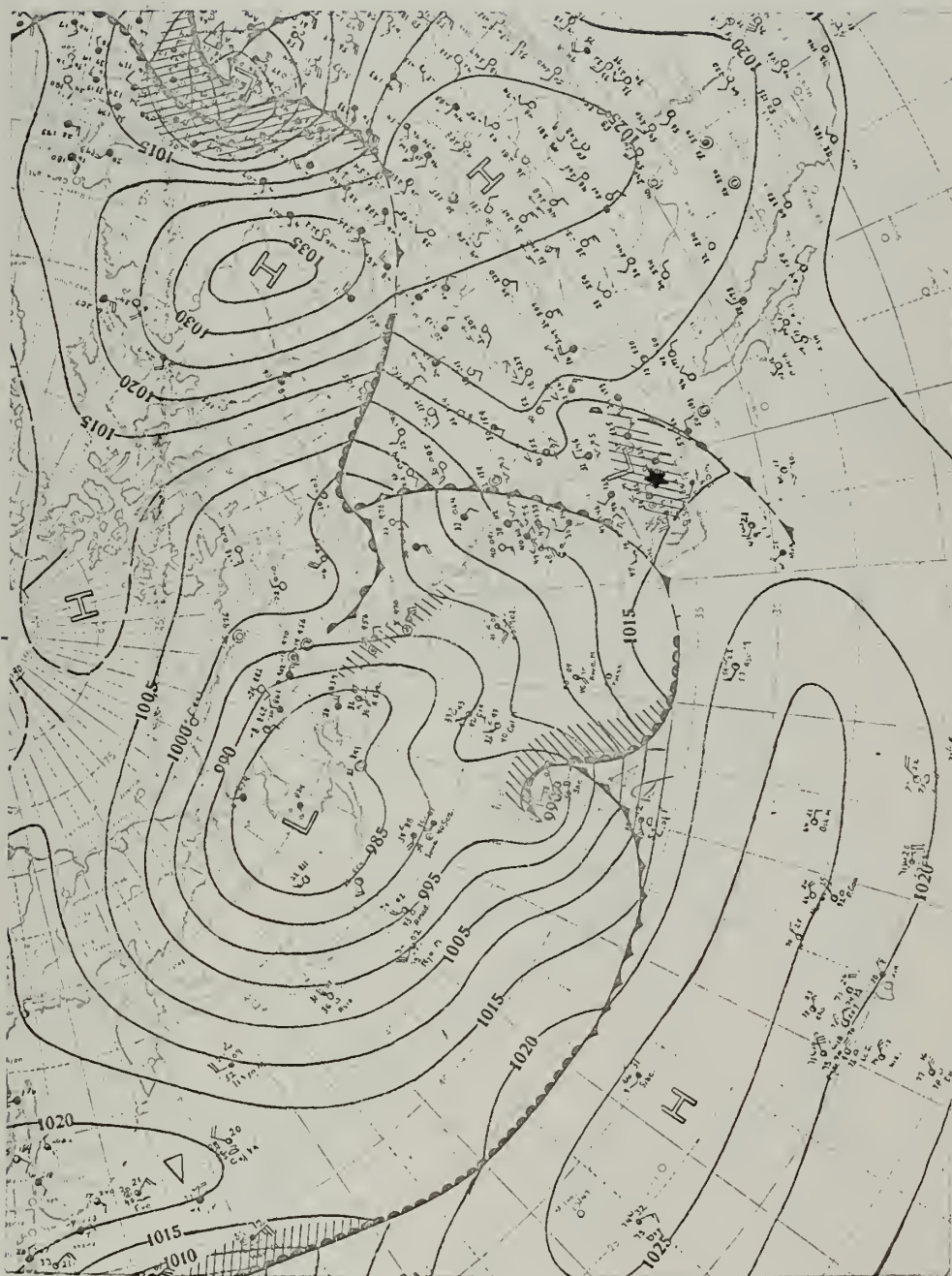


Fig. 12e. Surface Weather Map 1200Z 25 December 1931.



Fig. 12f. Surface Weather Map 1200Z 26 December 1931.



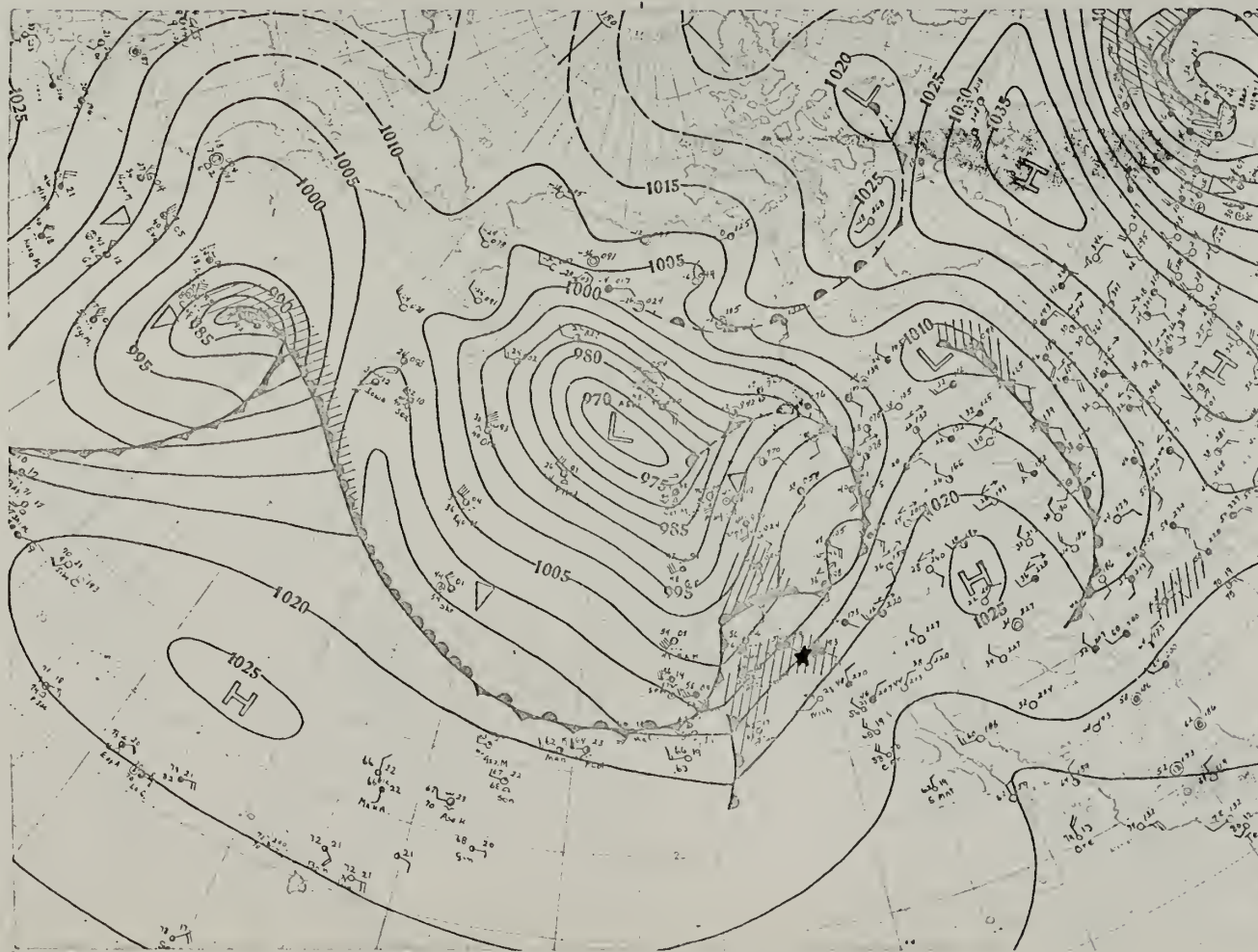


Fig. 12g. Surface Weather Map 1200Z 27 December 1931.

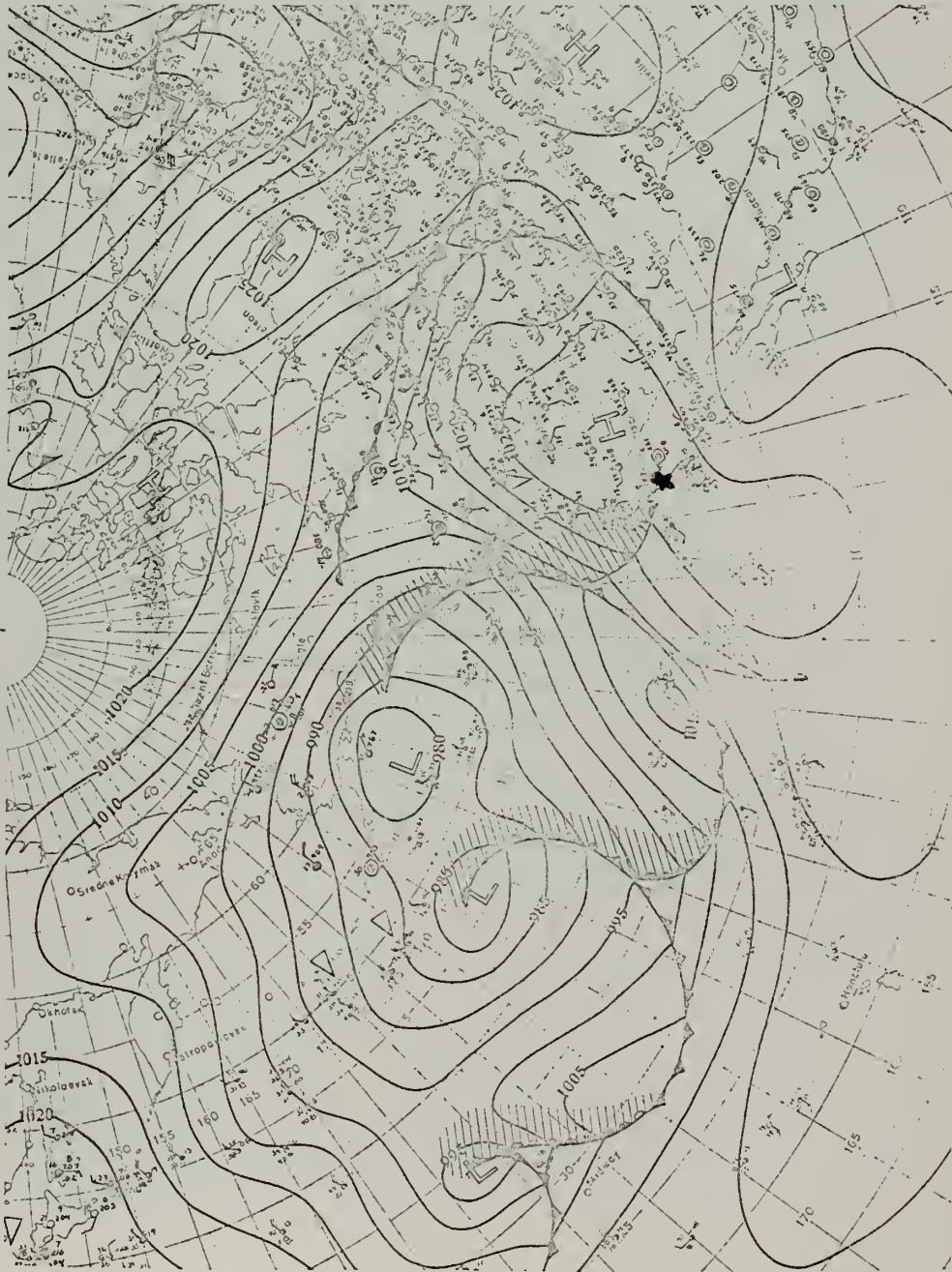


Fig. 13a. Surface Weather Map 1200Z 7 February 1926.

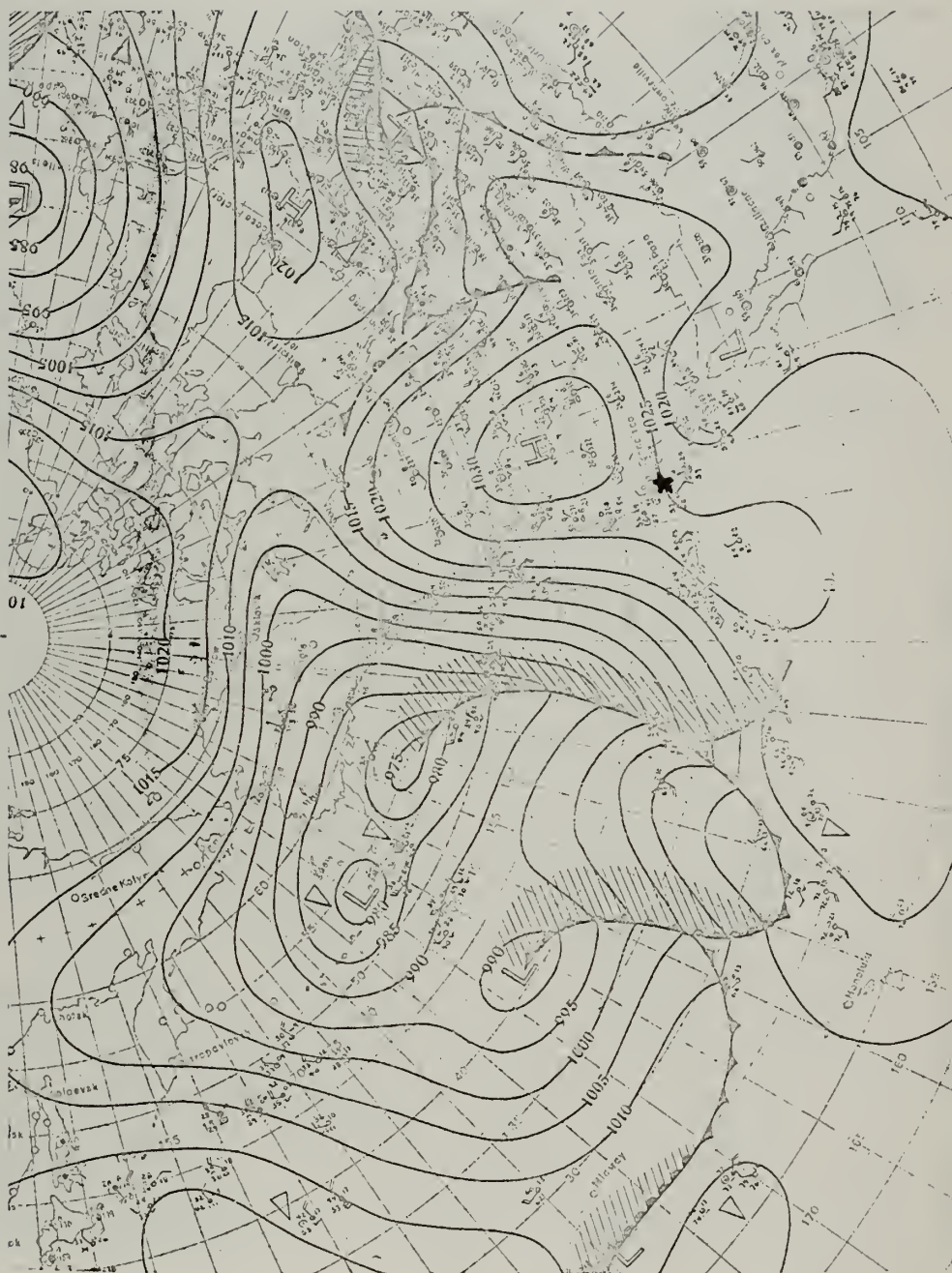






Fig. 13c. Surface Weather Map 1200Z 9 February 1926.



Fig. 13d. Surface Weather Map 1200Z 10 February 1926.





Fig. 13e. Surface Weather Map 1200Z 11 February 1926.



Fig. 13f. Surface Weather Map 1200Z 12 February 1926.

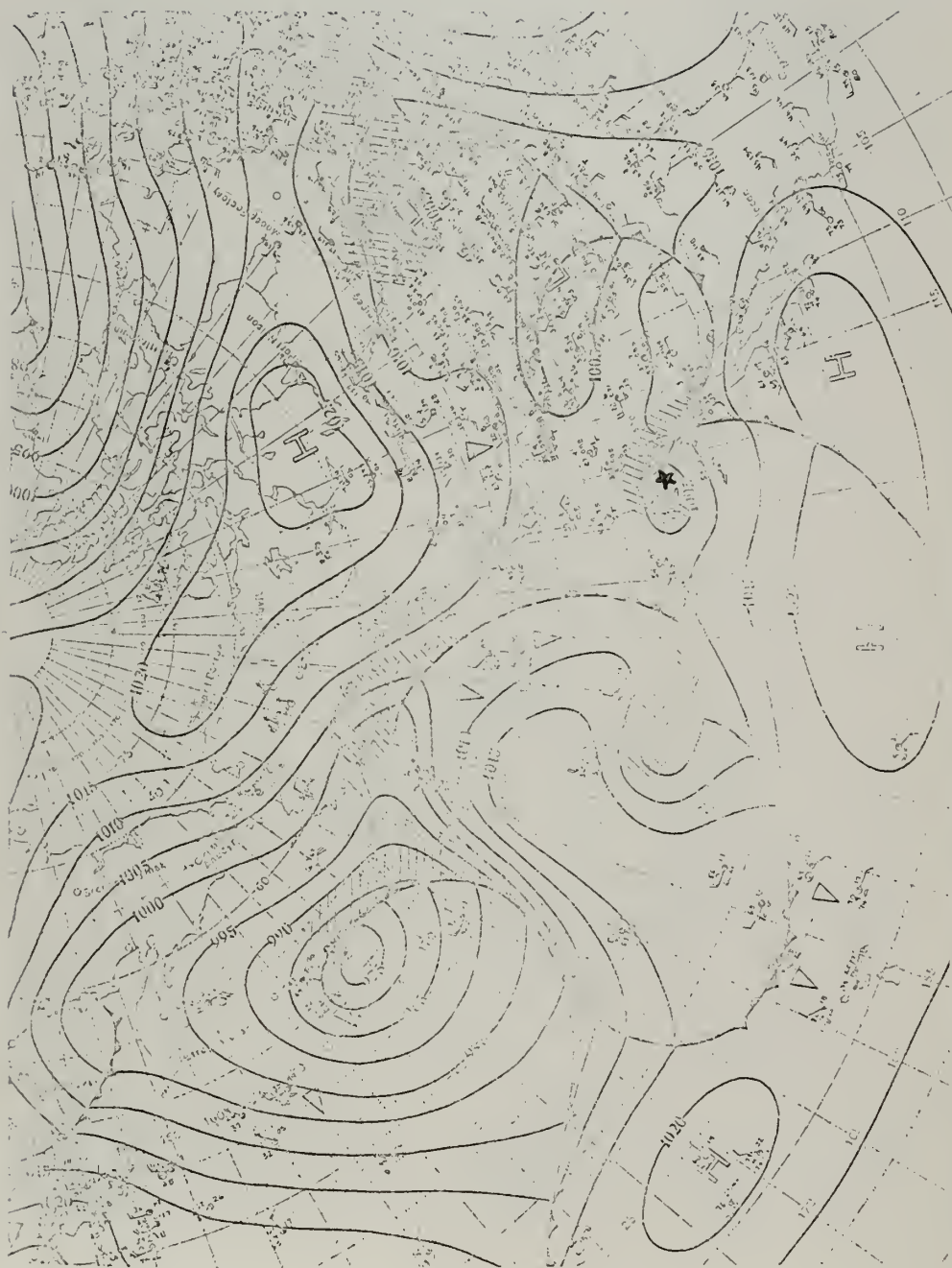


Fig. 13g. Surface Weather Map 1200Z 13 February 1926.







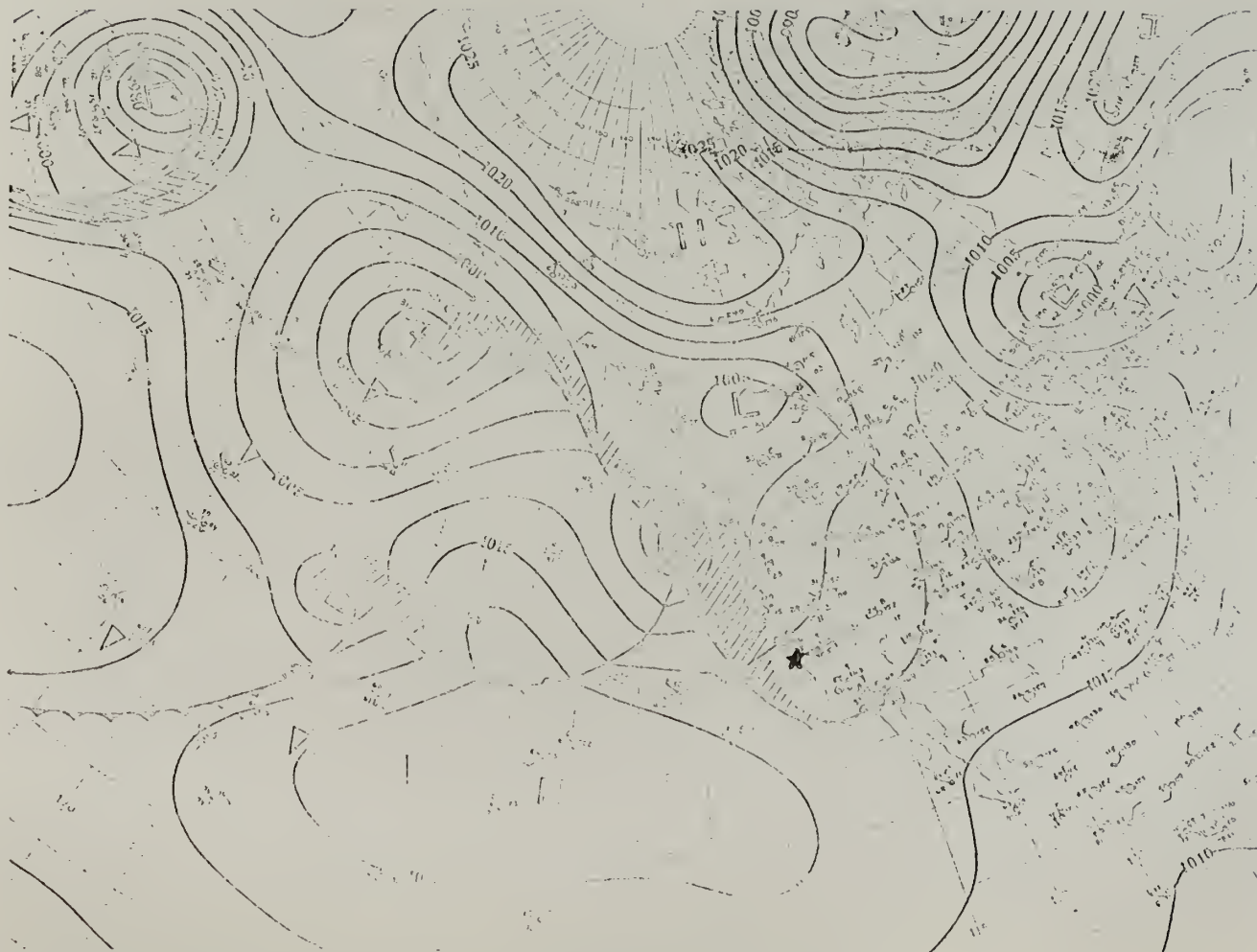


Fig. 13i. Surface Weather Map 1200Z 15 February 1926.

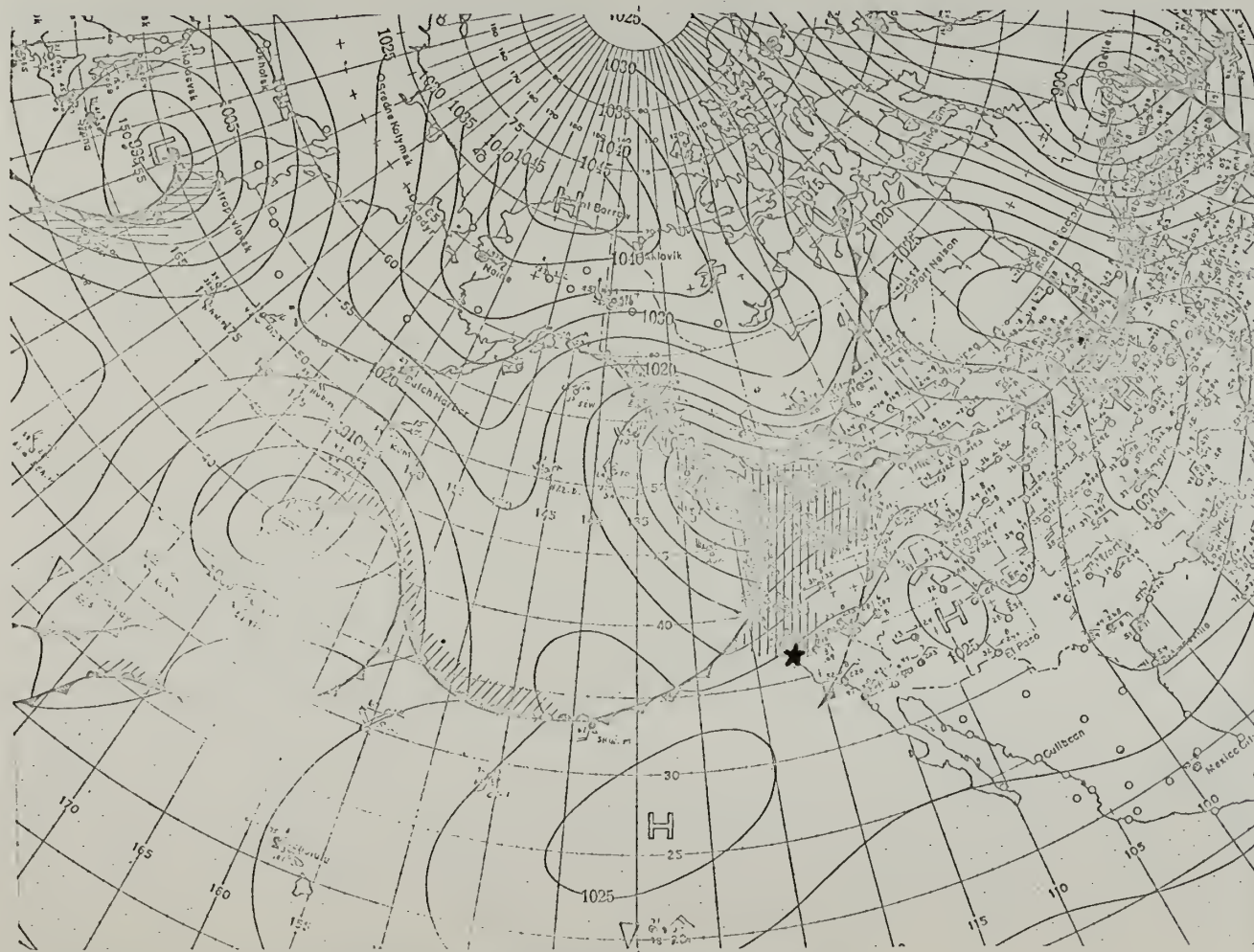


Fig. 14a. Surface Weather Map 1200Z 23 January, 1916.

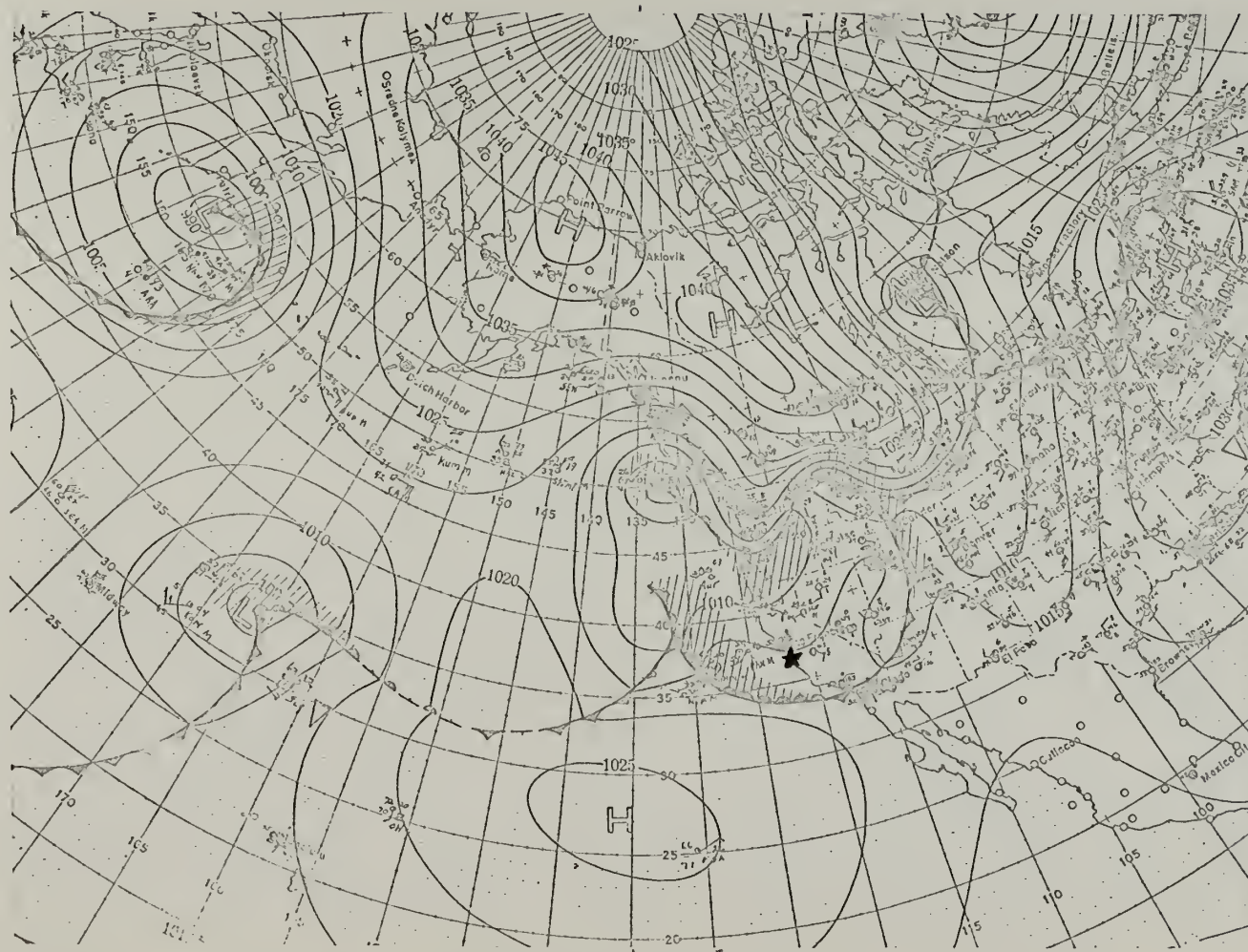


Fig. 14b. Surface Weather Map 1200Z 24 January 1916.



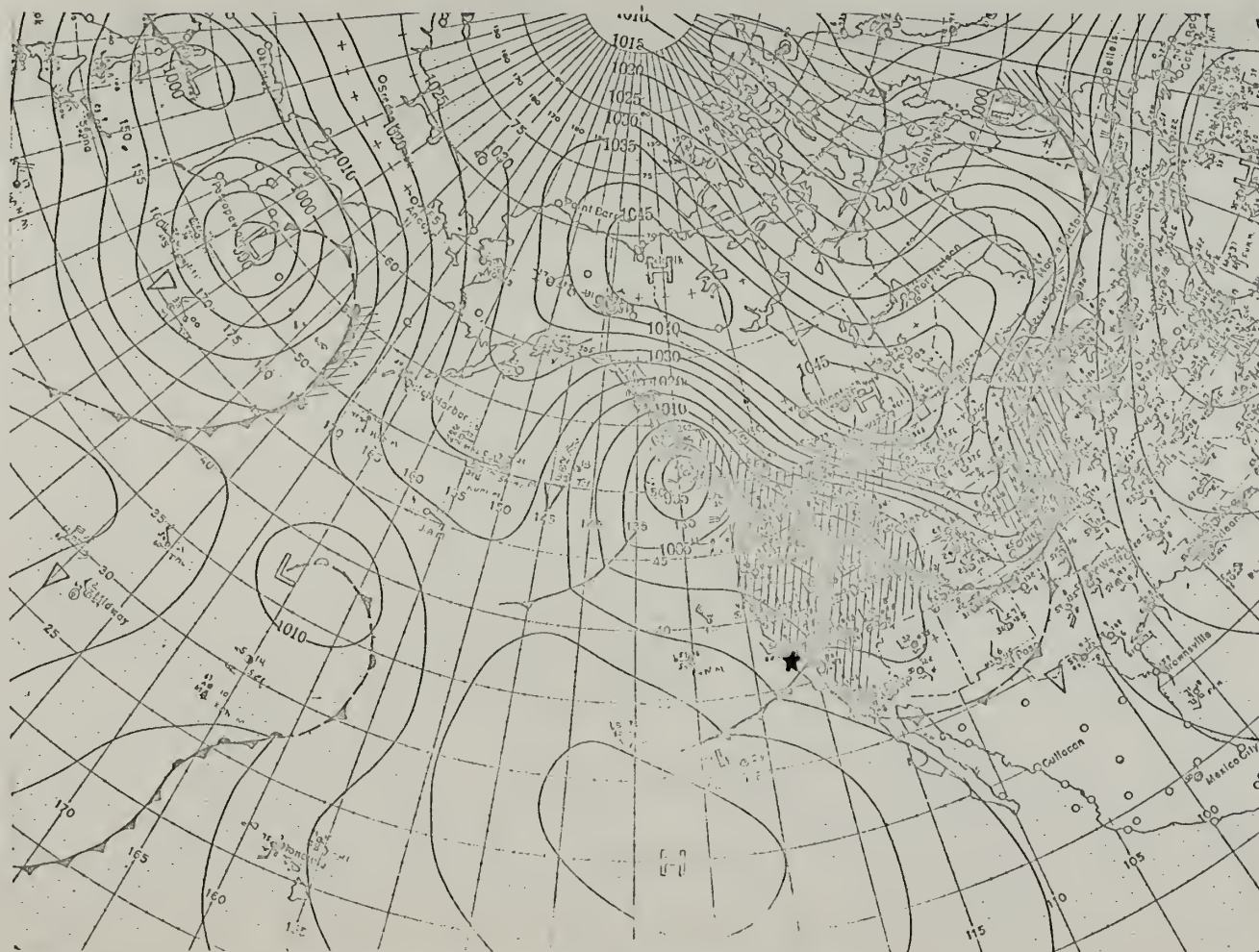


Fig. 14c. Surface Weather Map 1200Z 25 January 1916.





Fig. 14d. Surface Weather Map 1200Z 26 January 1916.

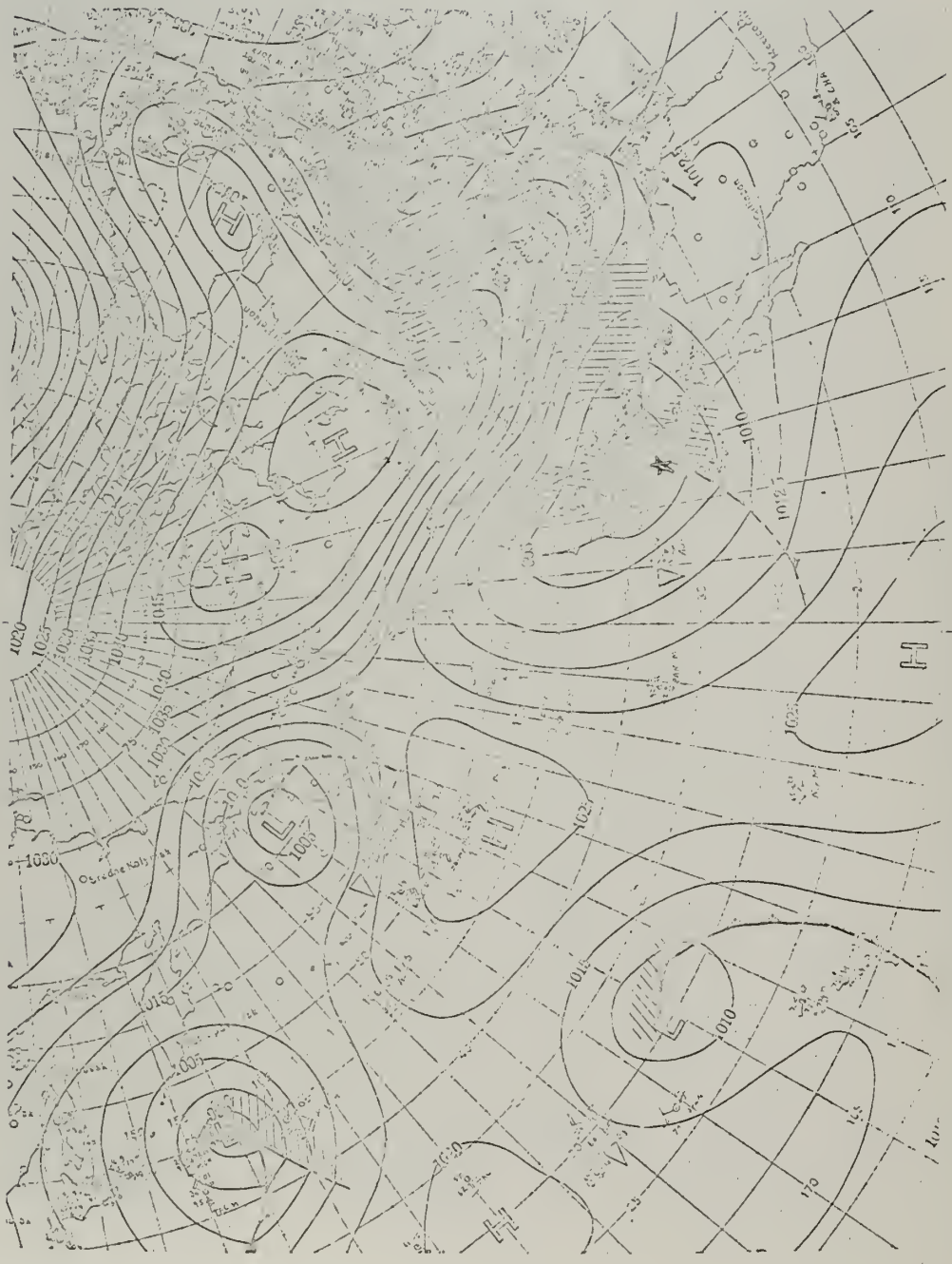


Fig. 14e. Surface Weather Map 1200Z 27 January 1916

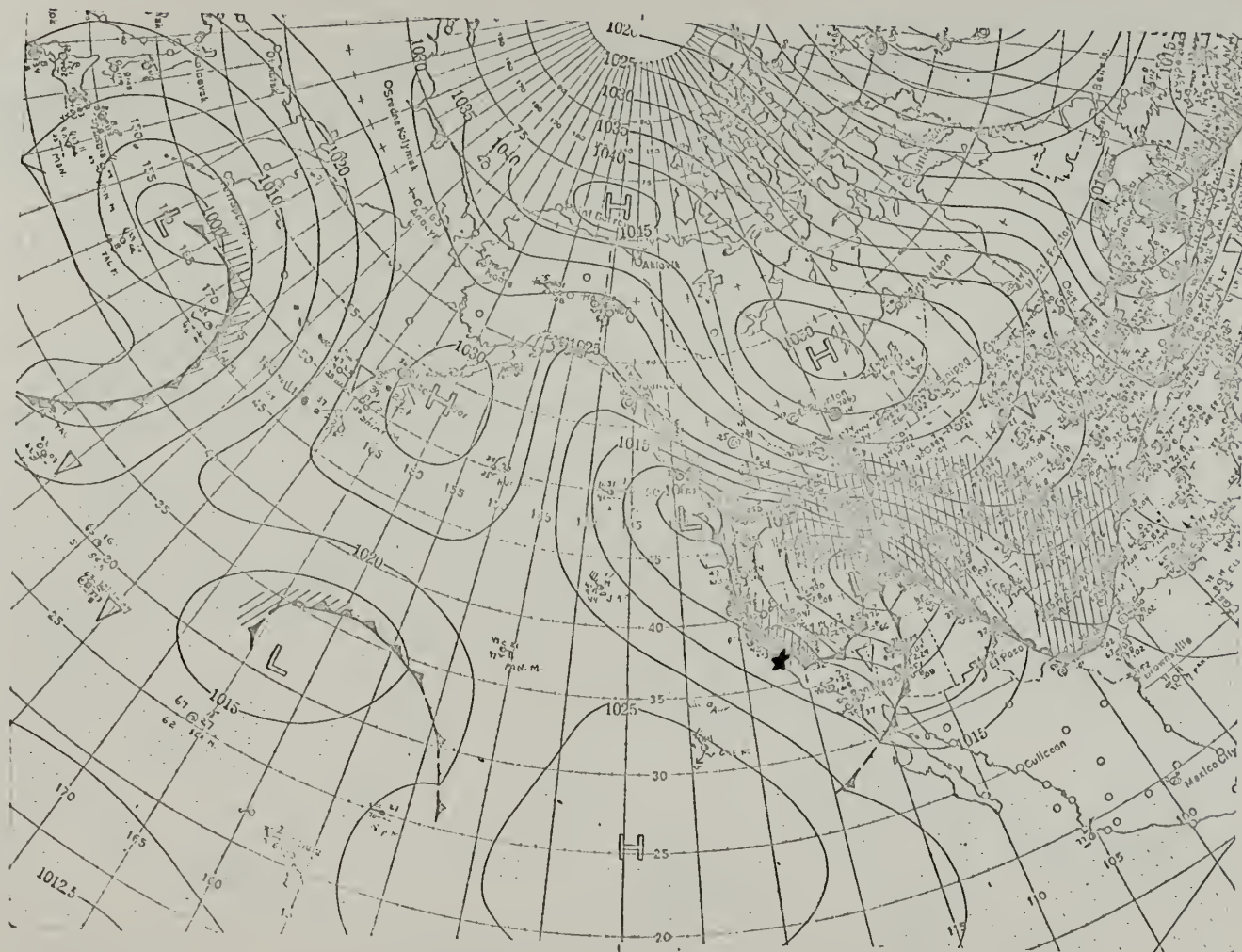


Fig. 14f. Surface Weather Map 1200Z 28 January 1916.



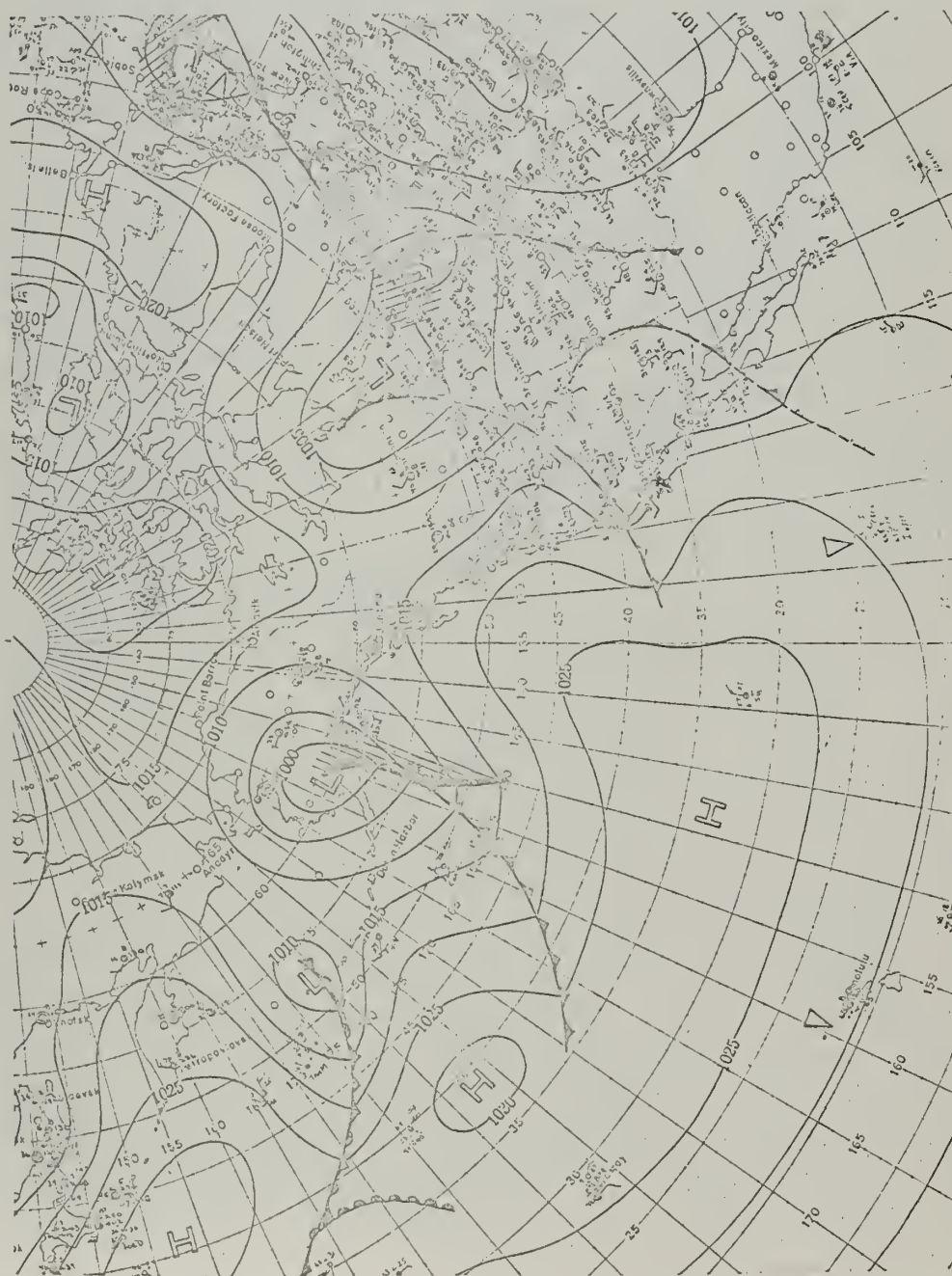


Fig. 15a. Surface Weather Map 1200Z 27 April 1915



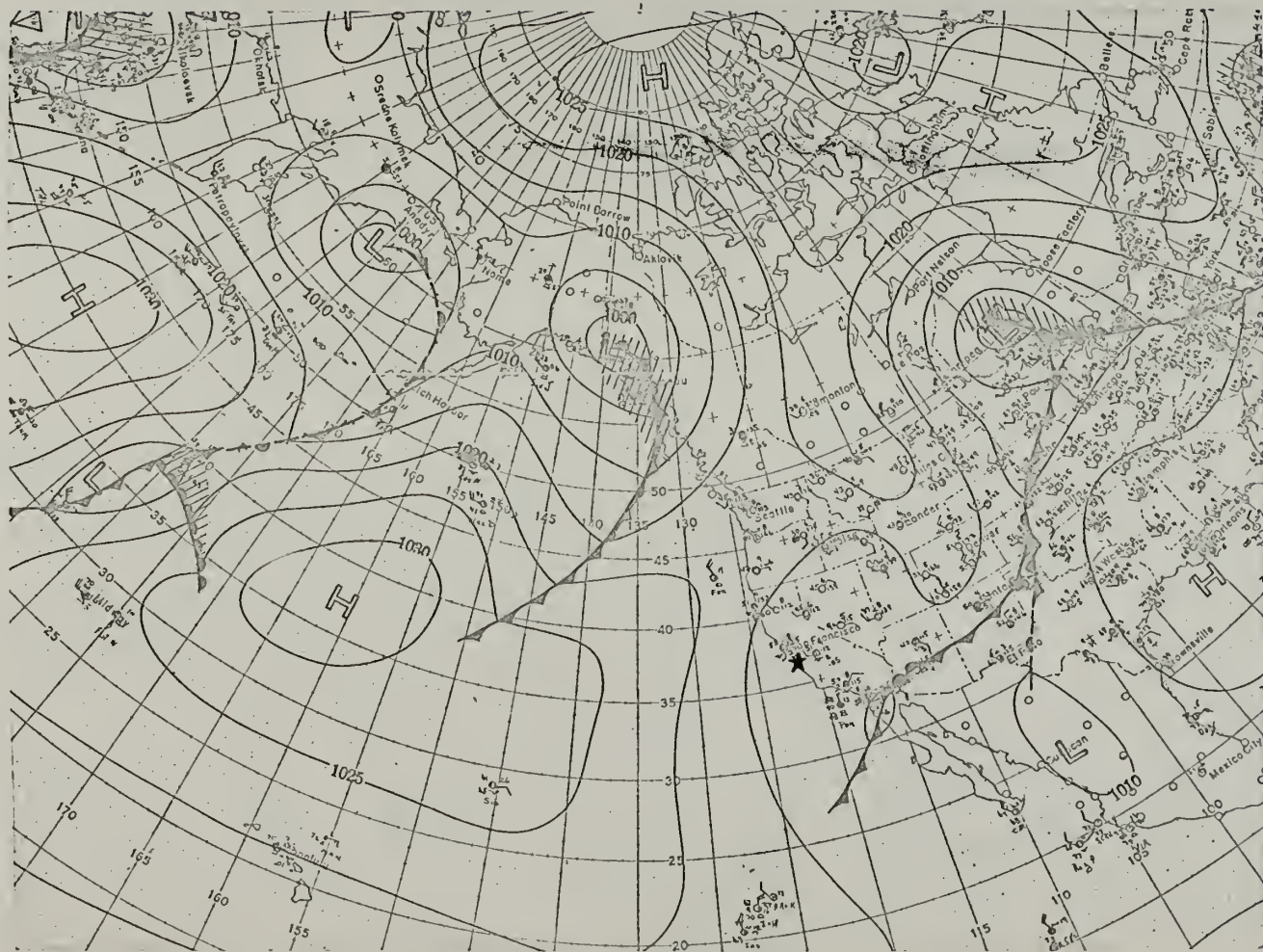


Fig. 15b. Surface Weather Map 1200Z 28 April 1915.

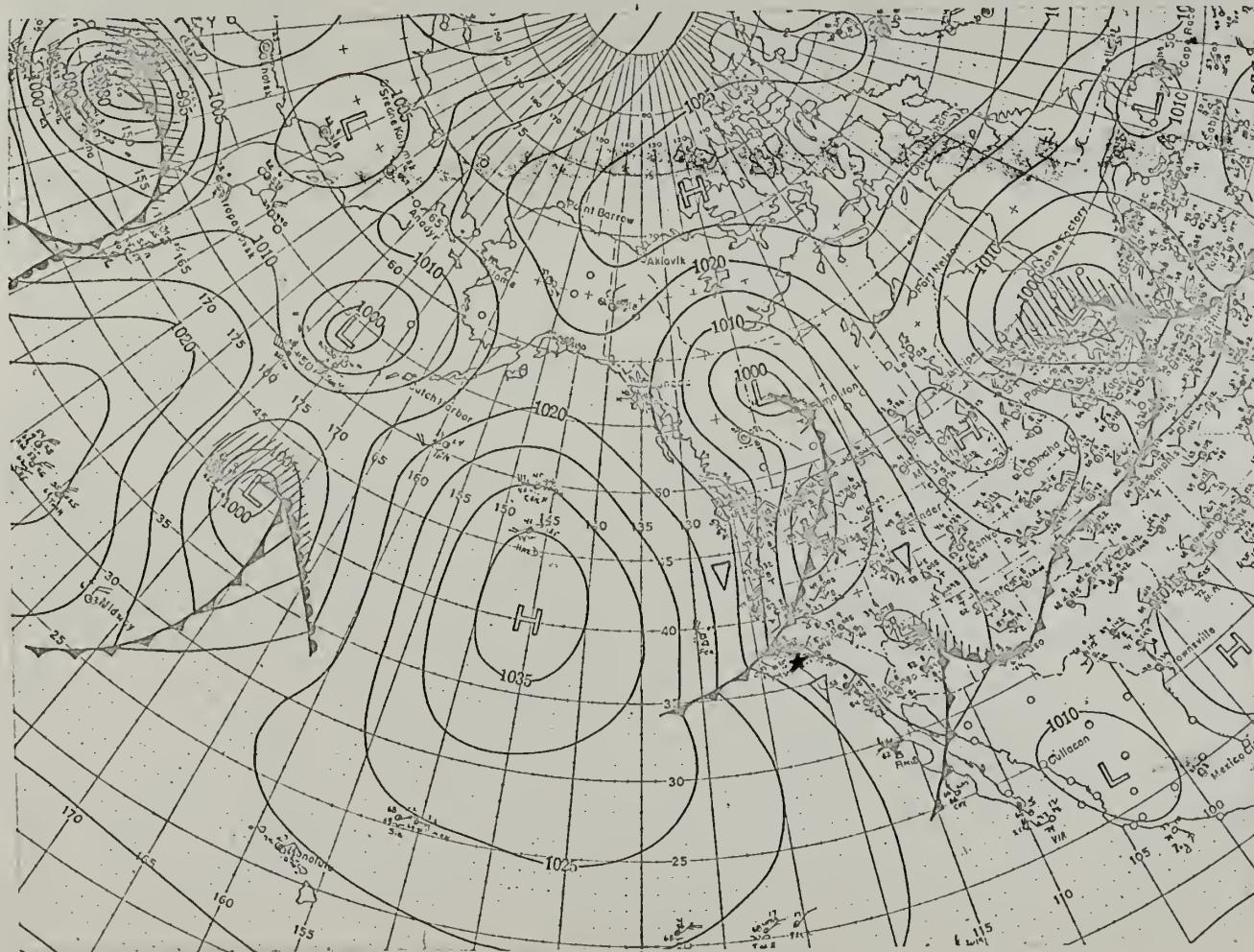


Fig. 15c. Surface Weather Map 1200Z 29 April 1915.





Fig. 15d. Surface Weather Map 1200Z 30 April 1915.

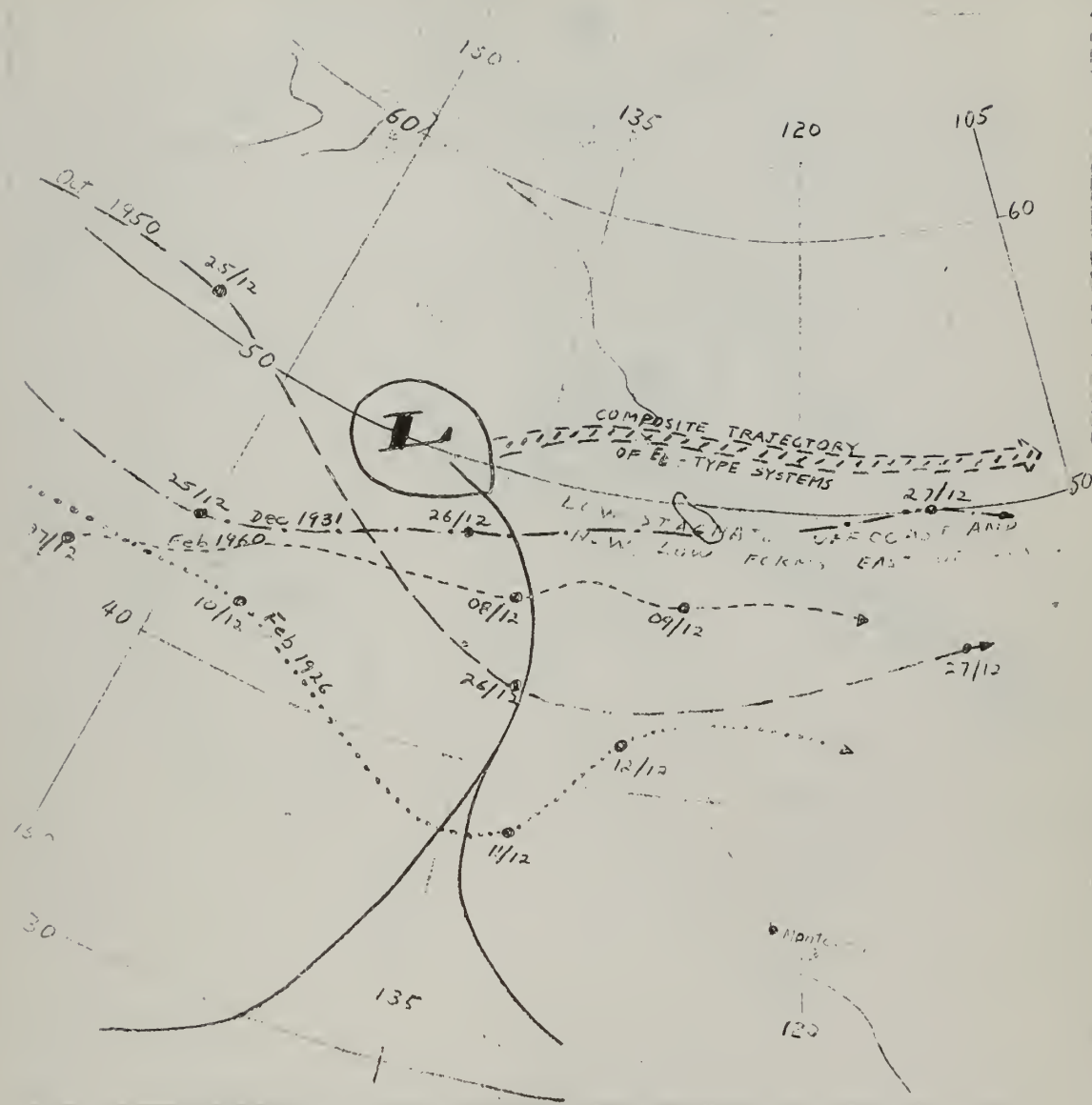


Fig 16 Schematic diagram of North American Zone 3 Weather Type E<sub>L</sub>.



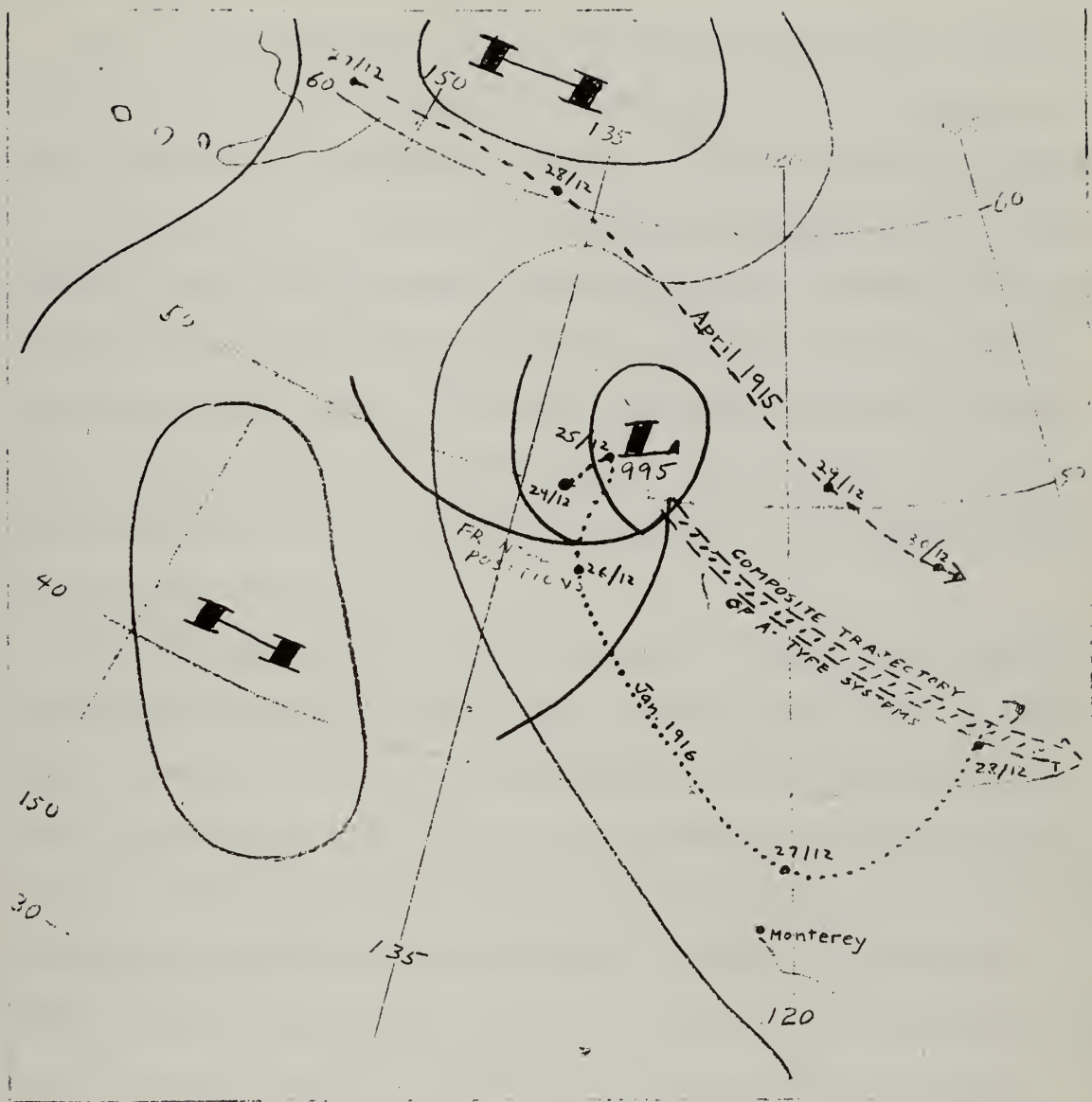


Fig. 17. Schematic diagram of North American Zone 3 Weather Type A.

## 6. Synoptic Situations Associated with Bay Wind Storms.

As in the previous section, a general description of the synoptic situations associated with each of the Bay Wind Storms is presented and these situations are classified according to Elliot's CIT Weather Types.

In addition to the general description, a surface pressure differential is given between Medford, Oregon and Fresno, California (465 miles), station numbers 597 and 389 respectively, and marked by arrows on the reproduced weather maps. This pressure gradient is measured over the region of the strong wind flow resulting in the Bay Wind Storms and is approximately normal to the general orientation of the surface isobars near the time of each storm.

Weather maps reproduced in this section are all of the 24-hourly Northern Hemisphere Historical Series with map times of 1200Z or 1230Z. Upper-air maps of this series were available in the case of the most recent storm and are also reproduced. In addition, 6-hourly synoptic surface or 1000-mb maps were obtained for the two most recent storms and information was extracted from these maps in order to present the synoptic situations in greater detail. All maps are presented at the end of this section in Figs. 18 through 25. As in the previous section, a star (★) indicates the approximate location of Monterey on each map.

The Bay Wind Storms were found to be associated with three North American Weather Types, which are shown in Figs. 26 through 28.

Description of the synoptic situations associated with the Bay Wind Storms follow:

Storm of 23 February 1953: 500-mb maps were available for this storm and the description of the synoptic situations therefore includes the upper-air picture. The 500-mb map time is 1500Z daily. Figs. 18a

through 18h depict these patterns.

The 500-mb map on the 21st shows a strong ridge extending northward into the Gulf of Alaska with a short-wave trough moving across it. A deep cold trough extends southwestward from Hudson Bay to southwest of Baja California. On the surface map at 1230Z the upper ridge appears as the eastern lobe of the Pacific anticyclone with an extension into the Great Basin. At 500 mbs on the 22nd the short-wave trough was over Washington State and a cut-off low had formed in the trough over Baja California. On the 23rd, the day of the storm, the ridge aloft had moved somewhat to the east and the short wave had moved into the cut-off low centering it over central California, where it deepened. On the 1230Z surface map on the 23rd may be seen the conditions that resulted in the high winds, with the surface high extending into southwestern Canada and a cold low on the surface over the central California-Nevada border. The packing of the isobars on the surface map indicated a pressure difference between Medford and Fresno of 24 mbs. On the 24th, at 1500Z, the short wave was moving out of the low at 500 mbs and the height of the center had already risen 200 feet. The 1230Z-surface map shows the surface low moving along with the upper trough and the pressure gradient only about half of the previous day's value. As indicated in Section 4, by 1230Z of the 24th the winds had diminished to normal values of speed. A study of 6-hourly 1000-mb charts indicates this pressure difference had significantly decreased to about 15 mbs by the time of the 1830Z map on the 23rd. The surface wind observations (Appendix V) also showed a significant decrease by that time (1030 PST).

The weather type associated with these conditions is a  $B_{N-C}$ , which persisted from 17 through 26 February. A schematic sketch of this type

is shown in Fig. 26.

Storm of 8-9 December 1943: The surface pattern for this storm was quite similar to the 1953 pattern, and is shown in Figs. 19a through 19d, 7 through 10 December. No upper-air maps were available, however, to complete the comparison. After 2 December an eastern extension of the Pacific anticyclone lay over the Great Basin. Surface fronts are seen on the maps moving down the West Coast from the Gulf of Alaska into central and southern California, suggesting short waves aloft. On the maps of the 5th and 6th, a surface low appeared, suggesting again the movement of a short wave into a cut-off low aloft. By the 7th this low had gone, but another front was moving down the coast. On the 9th at 1230Z a surface-low center again formed, this time over southern California, but the isobar packing was in the vicinity of Monterey with a Medford-Fresno pressure difference of 23 mbs. This situation must have existed for at least six hours, as a study of 6-hourly maps shows a 24-mb difference at 0630Z, near to the time the storm was reported to have struck. A strong pressure gradient remained on the 10th, but the orientation had changed so that northerly winds were no longer produced.

The weather type assigned for this storm was a  $B_{N-C}$  throughout the period of time studied.

Storm of 24-25 December 1942: The synoptic situation as seen on the surface maps on the day of the storm shows similarity with those already discussed, but it is difficult to trace the pattern as it developed from the previous days. The surface maps for 23 through 26 December are depicted in Figs. 20a through 20d. On the map of the 25th, the day of the storm, a tight pressure gradient may be seen, but it was oriented east-west with high pressure offshore and moderately low pressure



covering the entire Great Basin. This situation would be expected to produce northwest winds, but this is neither confirmed nor denied by the vague description in the newspapers. Measuring the pressure differential over a 465-mile east-west line centered at Monterey produces a value of about 16 mbs. It should be noted that this line does not coincide with the Medford-Fresno line, but rather is almost perpendicular to it. This procedure was necessary in this case, since a glance at Fig. 20c will show that the Medford-Fresno gradient was nearly zero. The difference, of course, is due to a north-south orientation of the isobars instead of the more usual east-west orientation. The distance over which this gradient was measured is the same as from Medford to Fresno. Intermediate maps were not available, so it was not possible to determine if this pressure gradient was a maximum. Map time is probably later than the time of maximum winds at Monterey.

There does not seem to be a clear-cut weather type present for the series of maps. On the basis of the surface situation, the pattern most closely resembles a  $B_{N-a}$  type, although it is very indefinite on the day of the storm. Type  $B_{N-a}$  is shown schematically in Fig. 27.

Storm of 20-21 November 1931: In this storm, as in December 1942, the synoptic situation is not as well defined as in the more intense storms. Figs. 21a through 21d show the series of surface maps from the 19th through the 22nd. On the 19th, the eastern lobe of the Pacific anti-cyclone extended inland over the Great Basin with a 1025-mb closed isobar. A series of cyclones was apparently moving eastward to the north of the high up to the point of crossing the coastline. The map of the 20th shows high pressure building up in far-western Canada and a large low-pressure area over the Rockies. By 1230Z on the 21st the low was centered

over the extreme southern portion of the Great Basin and high pressure had spread southward to the extreme northern portion of the Great Basin as well as offshore from the coast of the United States. The pressure differential was about 16 mbs between Fresno and Medford.

Elliot's weather typing indicates a B type (see Fig. 28) on the 19th, and then a  $B_{N-a}$  at least through the 22nd.

Storm of 20 February 1931: Figs. 22a through 22d depict the surface synoptic conditions from the 18th through the 21st. The map of the 18th shows a weak basin high, which had been more or less established since the 16th. A fairly continuous series of low-pressure centers is shown moving eastward on the 18th in what was probably a very strong zonal flow aloft. The deep trough which appears on the map of the 19th had become a closed low on the 20th, and a wedge of high pressure had pushed into the Great Basin as the trough moved southward. The Medford-Fresno pressure difference was about 12 mbs, and this map represents the situation within a few hours of the time the peak winds were at Monterey. On the 21st, the low moved eastward and the pressure gradient diminished. It is not too difficult here to visualize a sequence aloft similar to the one for February 1953.

The appropriate weather type for the dates 16 through 19 February is  $E_L$ , with  $B_{N-a}$  beginning on the 20th and continuing for at least the succeeding three days.

Storm of 30 November - 1 December 1923: Beginning on the 25th of November, high pressure existed over the Great Basin, very likely due to the existence of a strong ridge aloft. The sequence of maps from the 28th of November through the 2nd of December is shown in Figs. 23a through 23e. On the maps of the 28th and 29th, a weak front may be seen

moving southward along the west coast. On the 30th, it appears strengthened again and lying in a fairly deep surface trough. A suggestion of a wave on the front is seen on the map. On the 1st of December this wave had developed into a closed low centered over San Diego, and the basin high had strengthened to 1030 mbs. This map, reflecting the conditions producing the high winds at Monterey, shows a Medford-Fresno pressure differential of 17 mbs. The low dissipated and drifted southeastward on the following maps. The map of the 2nd further suggests a complete cut-off of the upper flow around the trapped low and a restoration of zonal flow aloft.

A  $B_{N-C}$  type prevailed through the 1st, followed by a B type.

Storm of 26-27 November 1919: The sequence of events for this storm did not develop as clearly as for some of the others, yet the synoptic conditions on both the 26th and 27th are almost classical as representative of the situation which apparently produces all storms of this type. Figs. 24a through 24d reproduce the maps of the 25th through the 28th. The Medford-Fresno pressure differential was 20 mbs on the 26th and about 19 mbs on the 27th. The gradient was further diminished as the low center moved off to the southeast on the 28th. The fact that the pressure gradient across Monterey appears to have been about the same both days, when only the map of the 27th reflected high winds, is probably explained by synoptic smoothing in drawing the maps. The Northern Hemisphere Series is designed primarily to describe the broad over-all synoptic conditions while it is believed that these wind storms are, at the most, mesoscale features.

Weather types appear to be  $B_S$  until the 24th, when the  $B_{N-C}$  type appears and prevails until the 28th. Subsequently a B type prevails,

reflecting once more zonal flow.

Storm of 4 October 1912: Maps reproduced in Figs. 25a through 25d represent the surface synoptic situation on the 2nd through the 5th of October 1912. The series very closely resembles the series of maps of February 1953 and the upper flow can be easily visualized. The primary difference is that the intensity as depicted by the pressure gradient across Monterey is considerably less, and the orientation is such as to produce a more northwesterly wind at Monterey on the day of the storm. Before the storm, high pressure extended northeastward from the Pacific anticyclone and troughs moved down the west coast and deepened in the central California region. On the map depicting the situation on the day of the storm, it can be seen that instead of a closed low on the surface only a trough was drawn. The pressure difference between Medford and Fresno was only about 11 mbs, and on the following day the difference was reduced to 8 mbs. In view of the considerably stronger gradients found to be associated with the wind storms previously discussed, it is difficult to explain this weakness. The gradient disappeared as the low (or trough in this case) moved off to the southeast.

Throughout the entire series of maps discussed, the weather type was  $B_{N-c}$ .

Discussion: Clearly, much closer resemblance among the eight Bay Wind Storms exists than occurs for the Open Ocean Storms. One feature stands out prominently in nearly all of these Bay Wind Storms, and that is the similarity in the relative positions between a high and a low-pressure center for each of the storms. In each case a fairly tight pressure gradient occurred over land, producing the high winds in the Monterey Bay region. Table 4, summarizing the weather type and the pressure gradient existing at storm time for each storm, shows that the  $B_N$  type prevailed,



with gradients ranging from 11 to 24 mbs.

The Santa Ana winds of southern California, similar in many respects to the type of winds studied here, have been frequently mentioned in the literature. Lockhart [11] pointed out that these offshore winds are nearly always northeast or east, and that they exist as a result of strong pressure gradients building up between the elevated plateau regions of the far western states and the Pacific Ocean. He further noted the surprise element that often accompanies them.

It is because of the similarity between the regional Santa Anas and Bay Wind Storms that the author has utilized a sea-level pressure-gradient variable as an indicator for the Bay Wind Storms. Sergius and Huntoon [12] employ a similar variable in their Santa Ana Wind forecast technique. Their approach to forecasting such a phenomenon could very well apply to the storm situations in Monterey Bay. However, the frequency of Bay Wind Storms for the period under study is considerably less than that of the well-known Santa Anas. This author believes that one of the main reasons for the fewer number is the much less favorable topography in the Monterey area. While narrow mountain passes funnel winds down from the high plateau regions directly to the coastal plain in the Santa Ana situation, no such circumstance exists for Monterey Bay.

To yield a pressure gradient of the strength and orientation associated with the Bay Wind Storms (Table 4), low pressure must exist in central or southern California. While nearly all of the wind storms of this study appear to be consistent in their association with Elliot's  $B_N$  weather type, it is noteworthy that this type does not indicate a low pressure center in those areas of California. Apparently this is a unique regional condition that locally modifies the basic  $B_N$  weather type for the conditions needed to produce the Bay Wind Storms.

	<u>Feb 1953</u>	<u>Dec 1943</u>	<u>Dec 1942</u>	<u>Nov 1931</u>	<u>Feb 1931</u>	<u>Nov 1923</u>	<u>Nov 1919</u>	<u>Oct 1912</u>
Weather Type	B <sub>Nc</sub>	B <sub>Nc</sub>	B <sub>Na</sub>	B <sub>Na</sub>	B <sub>Na</sub>	B <sub>Nc</sub>	B <sub>Nc</sub>	B <sub>Nc</sub>
Gradient	24 mb	24 mb	16 mb <sup>1</sup>	16 mb	12 mb	17 mb	20 mb	11 mb

<sup>1</sup> Gradient measured over 465-mile east-west line centered on Monterey.

Table 4. Summary of Synoptic Conditions for Bay Wind Storms.

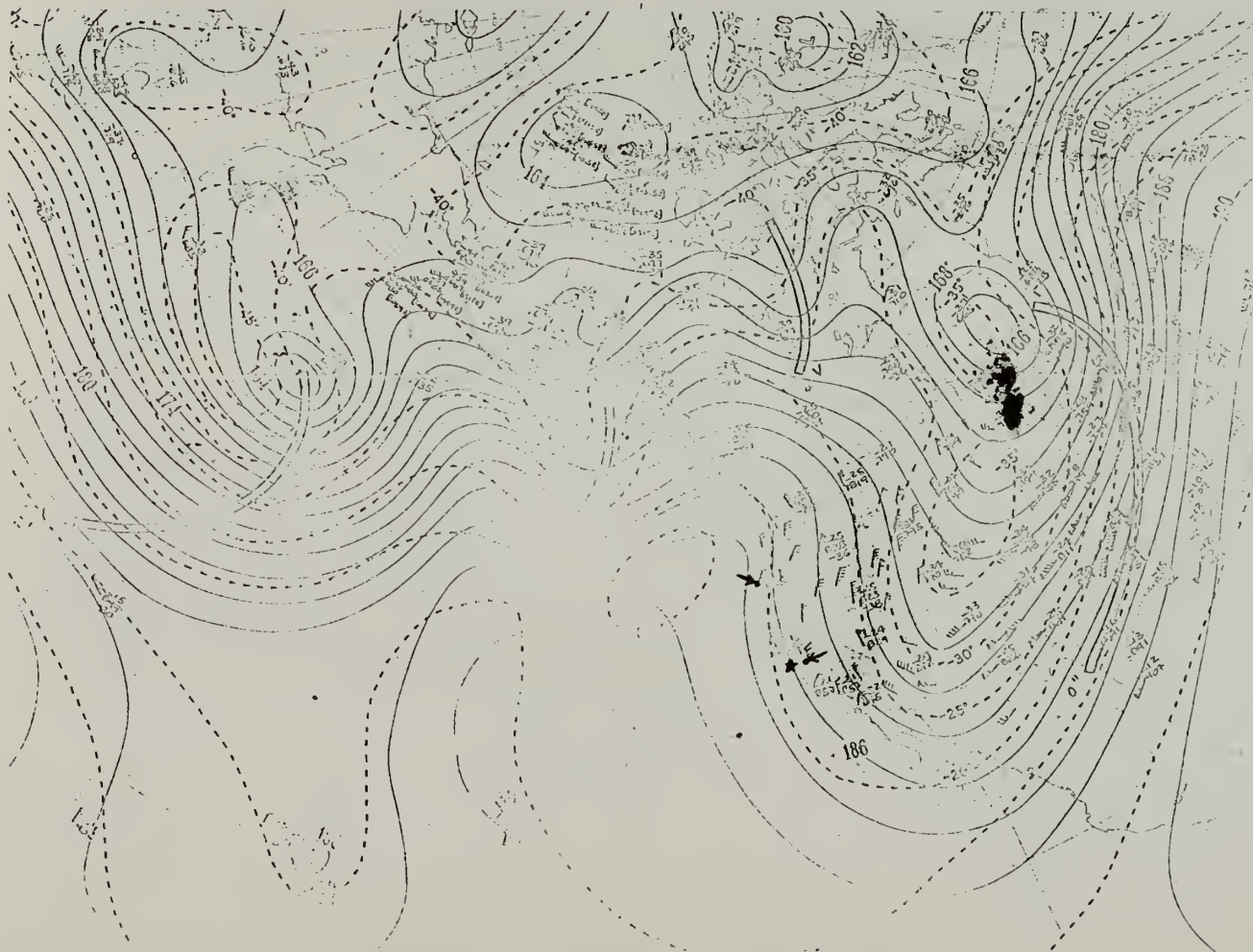


Fig. 18a. 500 mb Weather Map 1500Z 21 February 1953.

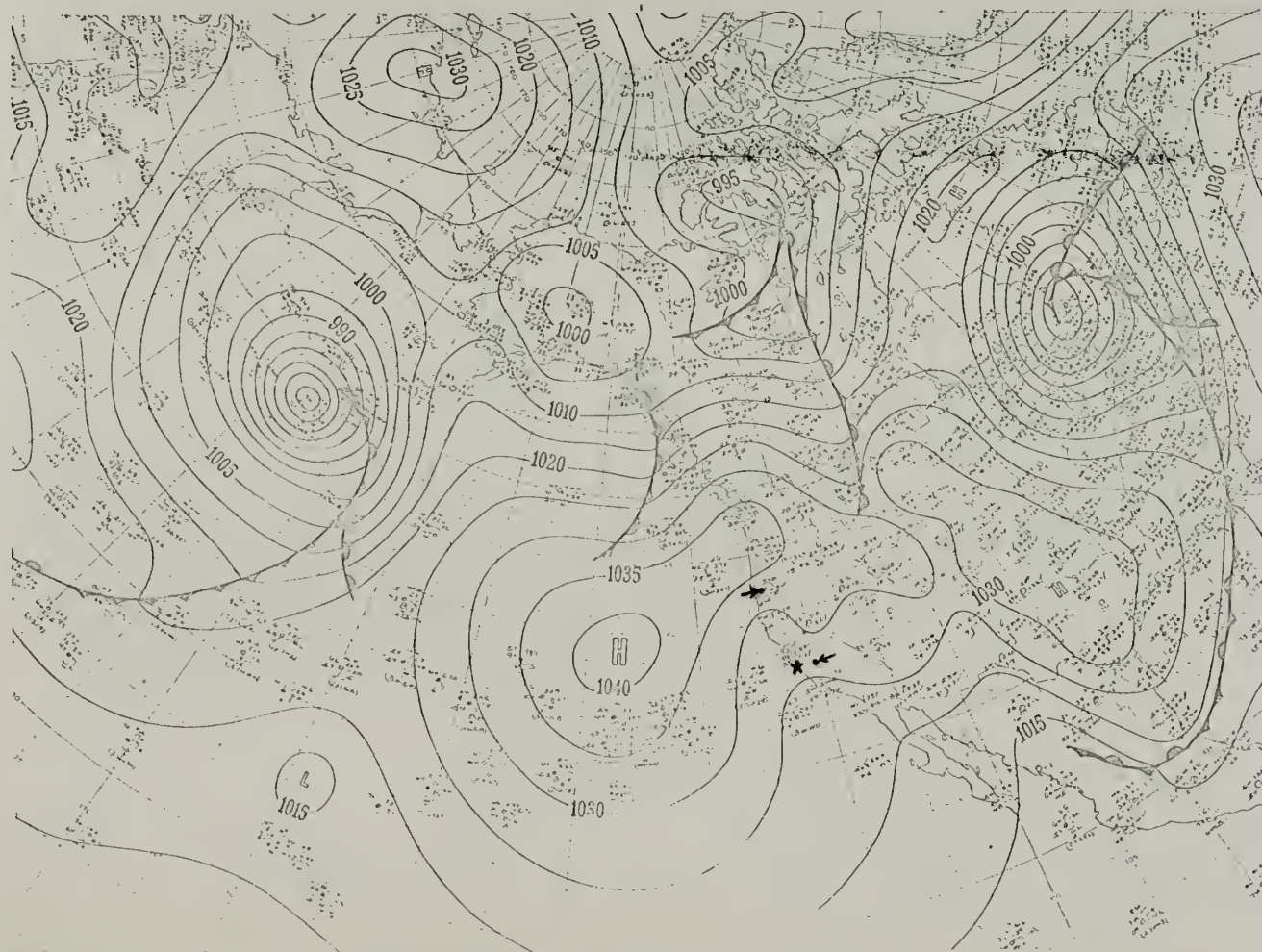


Fig. 18b. Surface Weather Map 1230Z 21 February 1953.





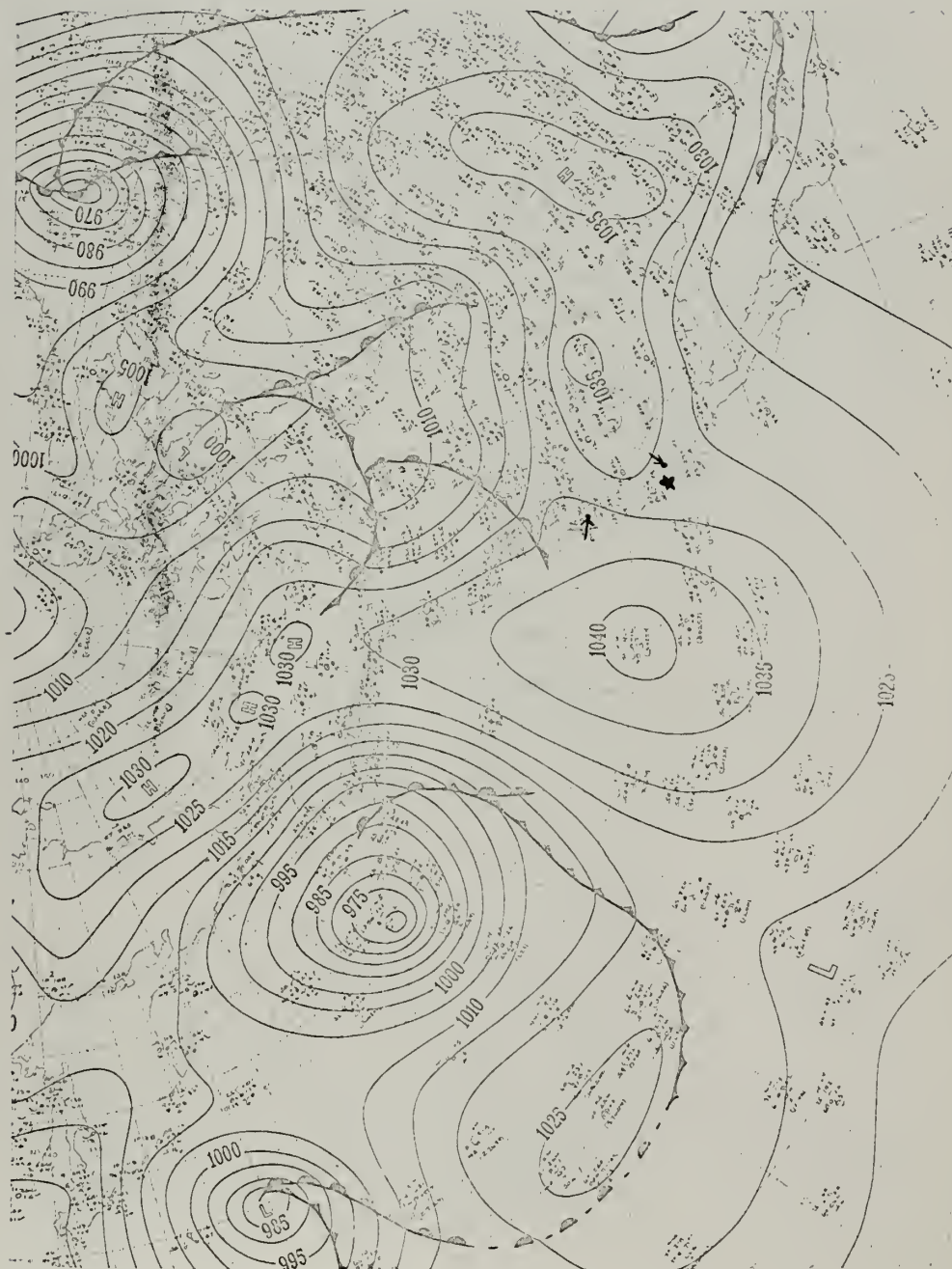


Fig. 18d. Surface Weather Map 1230Z 22 February 1953.

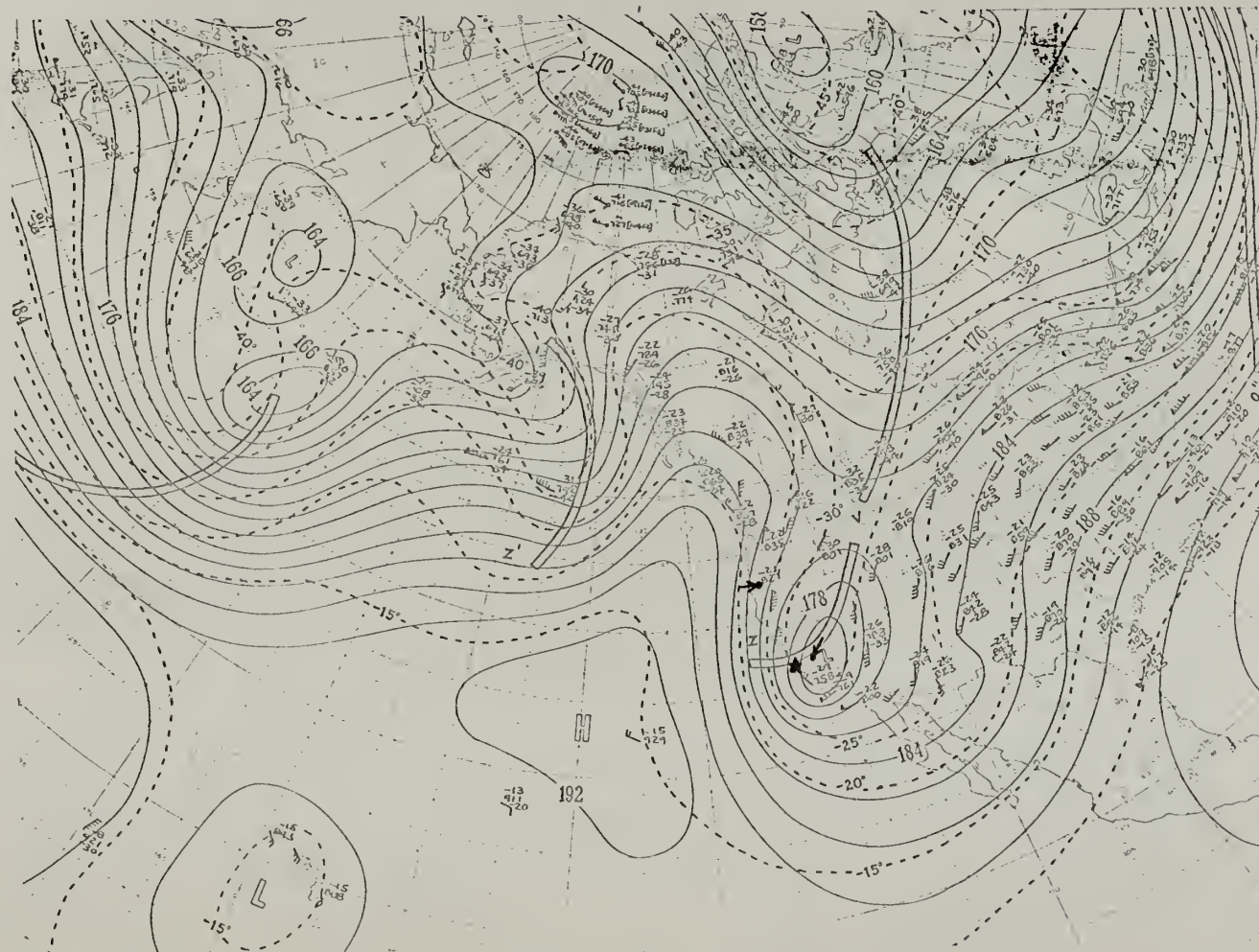


Fig. 18e. 500 mb Weather Map 1500Z 23 February 1953 (Date of storm).



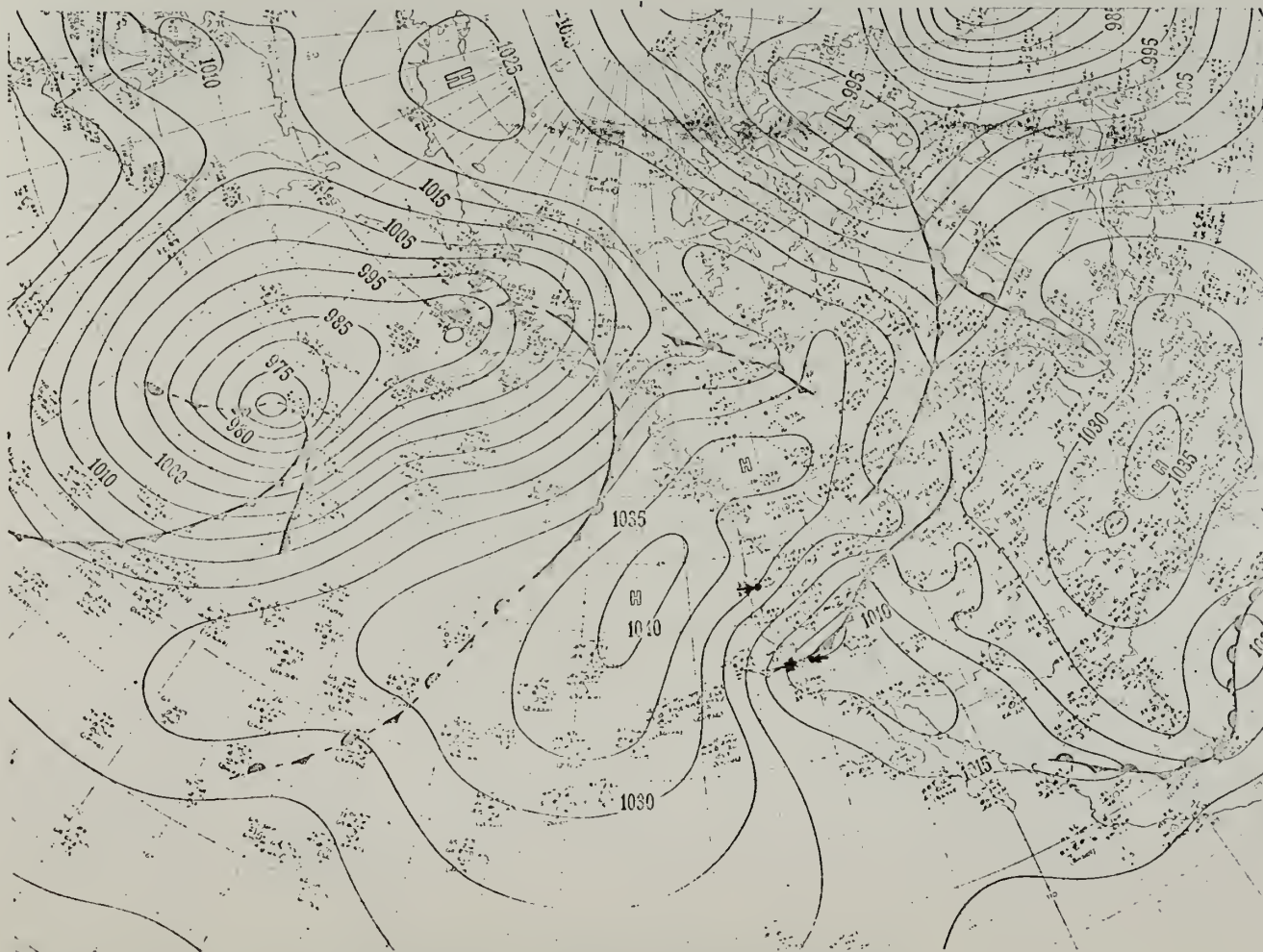


Fig. 18f. Surface Weather Map 1230Z 23 February 1953 (Date of storm).



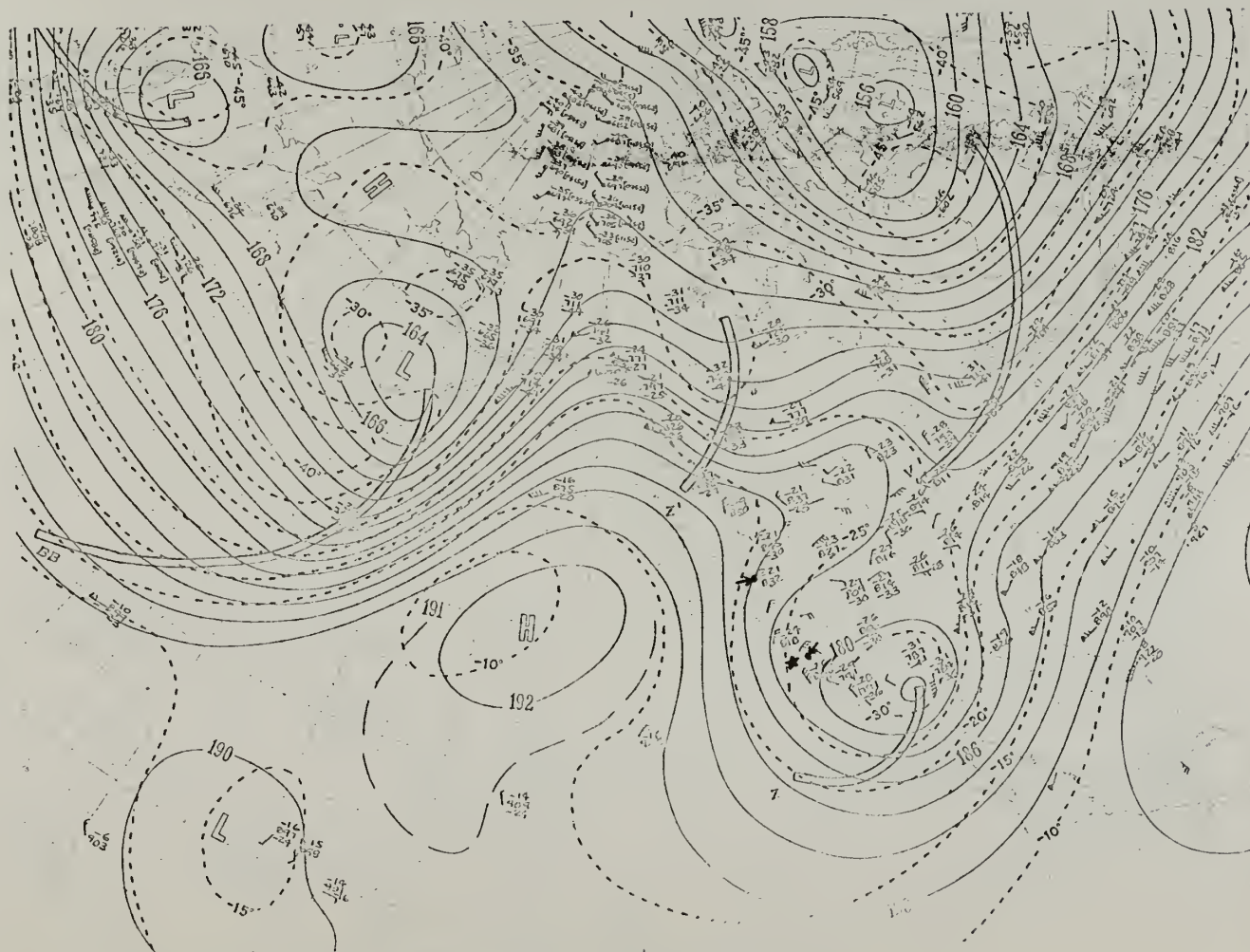
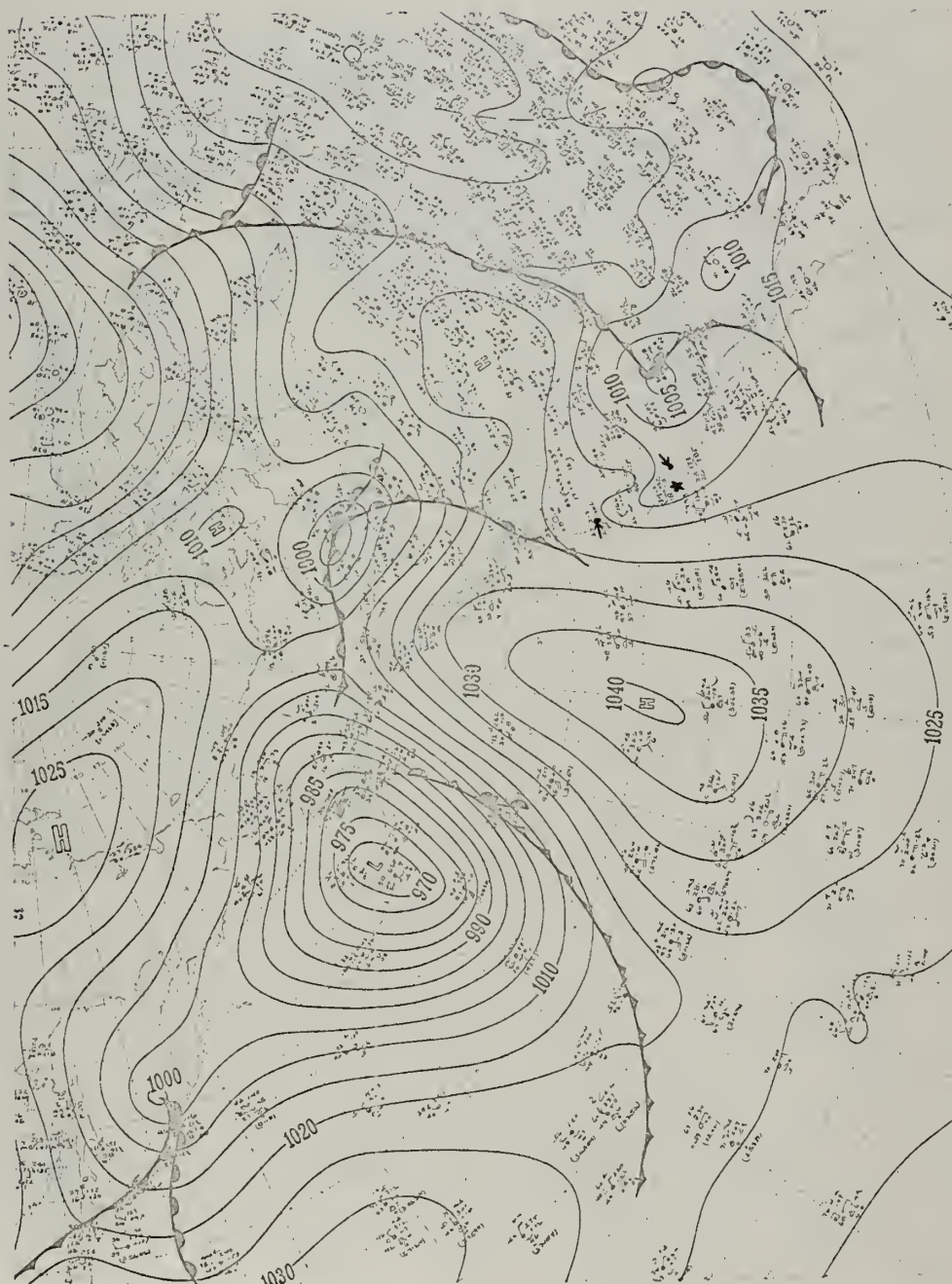


Fig. 18g. 500 mb Weather Map 1500Z 24 February 1953.



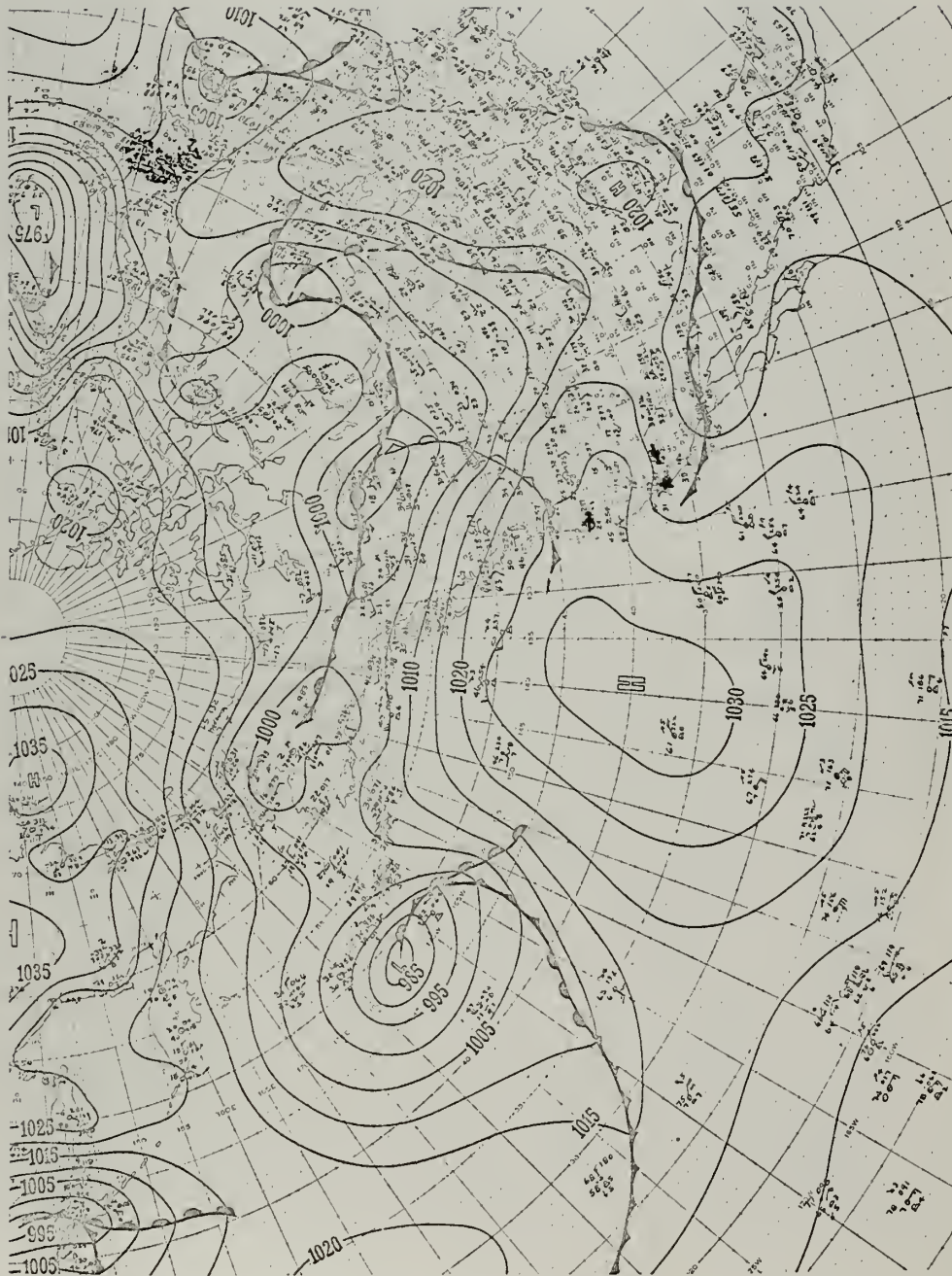


Fig. 19a. Surface Weather Map 1230Z 7 December 1943.







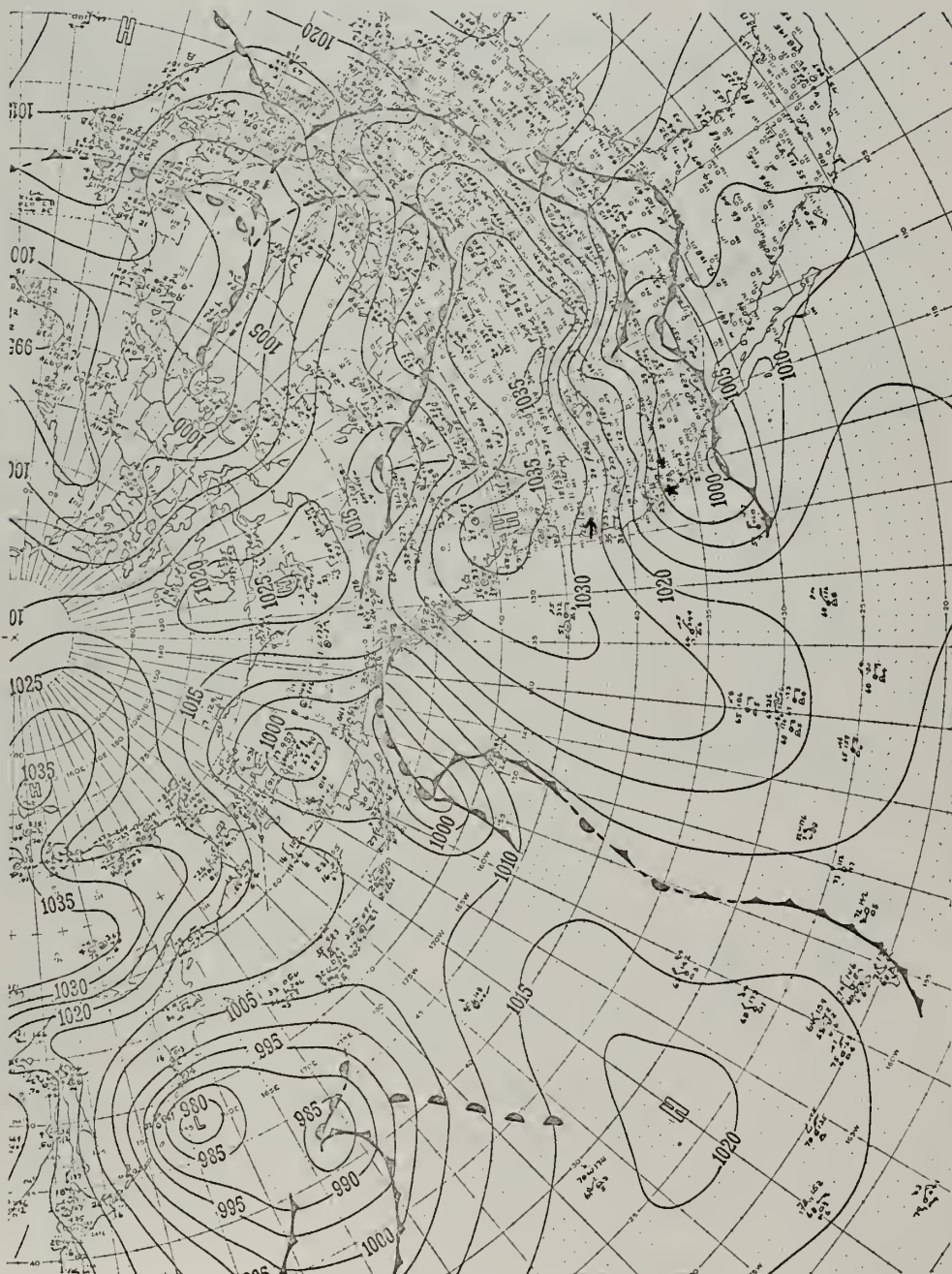


Fig. 19c. Surface Weather Map 1230Z 9 December 1943.

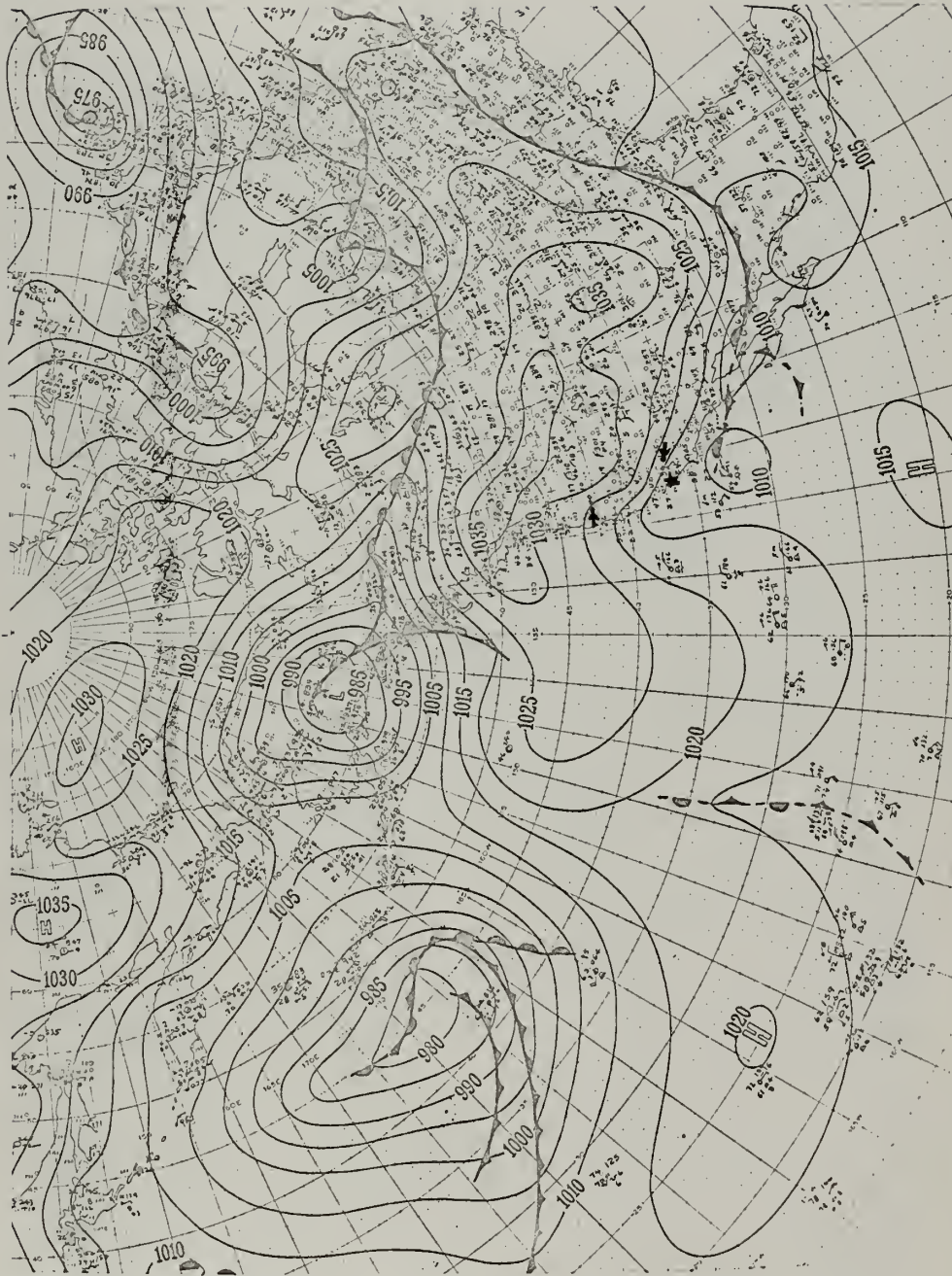


Fig. 19d. Surface Weather Map 1230Z 10 December 1943.



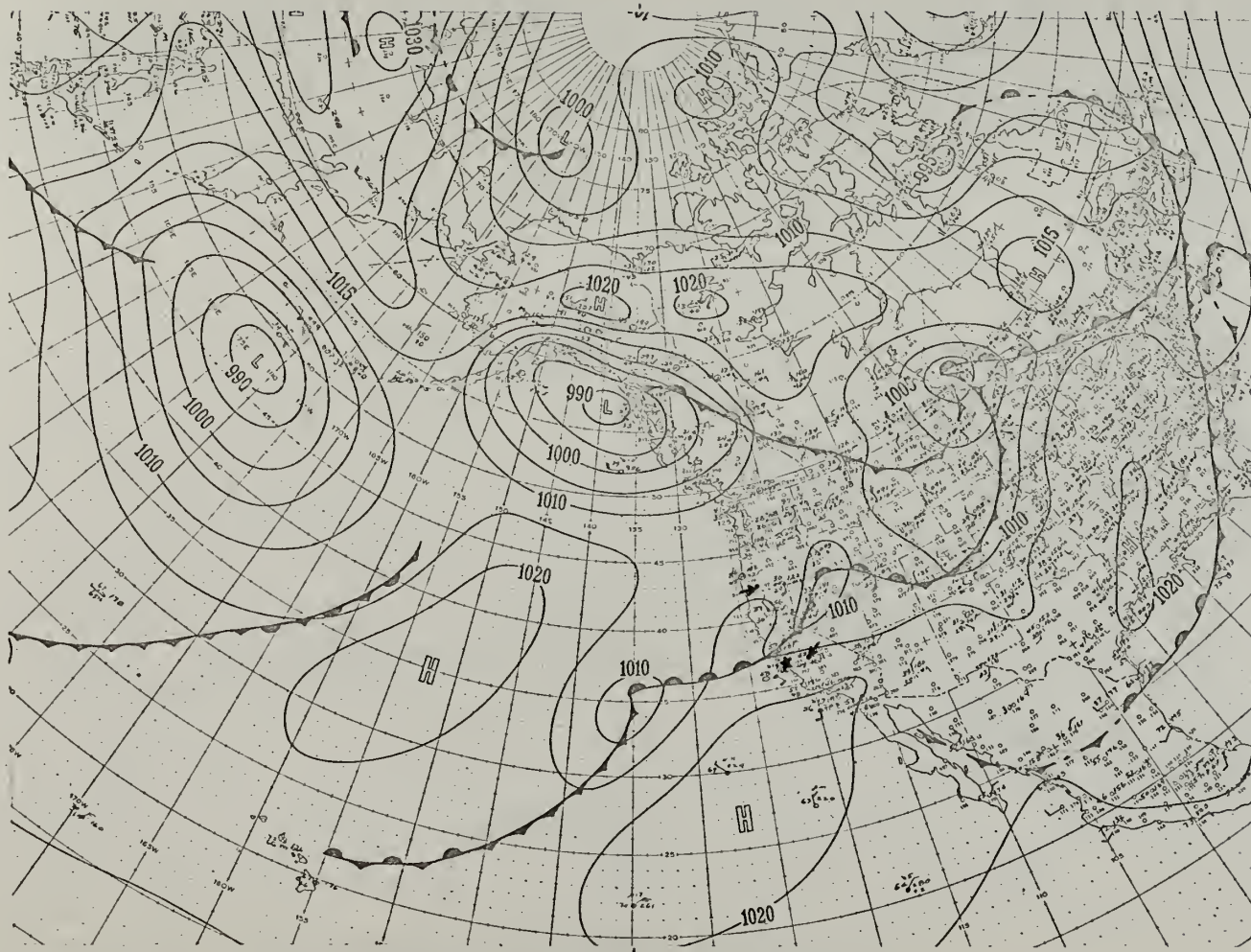


Fig. 20a. Surface Weather Map 1230Z 23 December 1942.

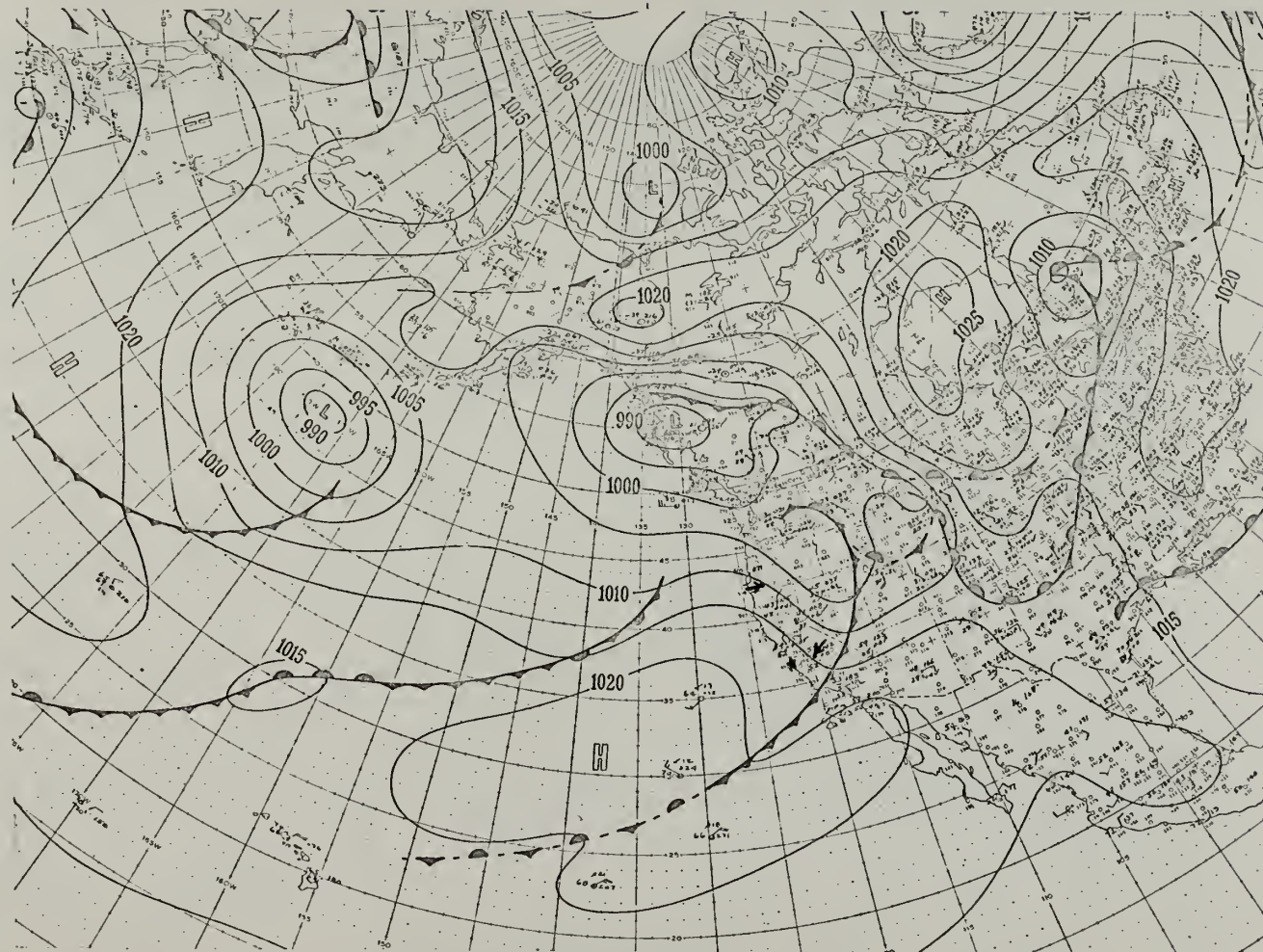


Fig. 20b. Surface Weather Map 1230Z 24 December 1942.



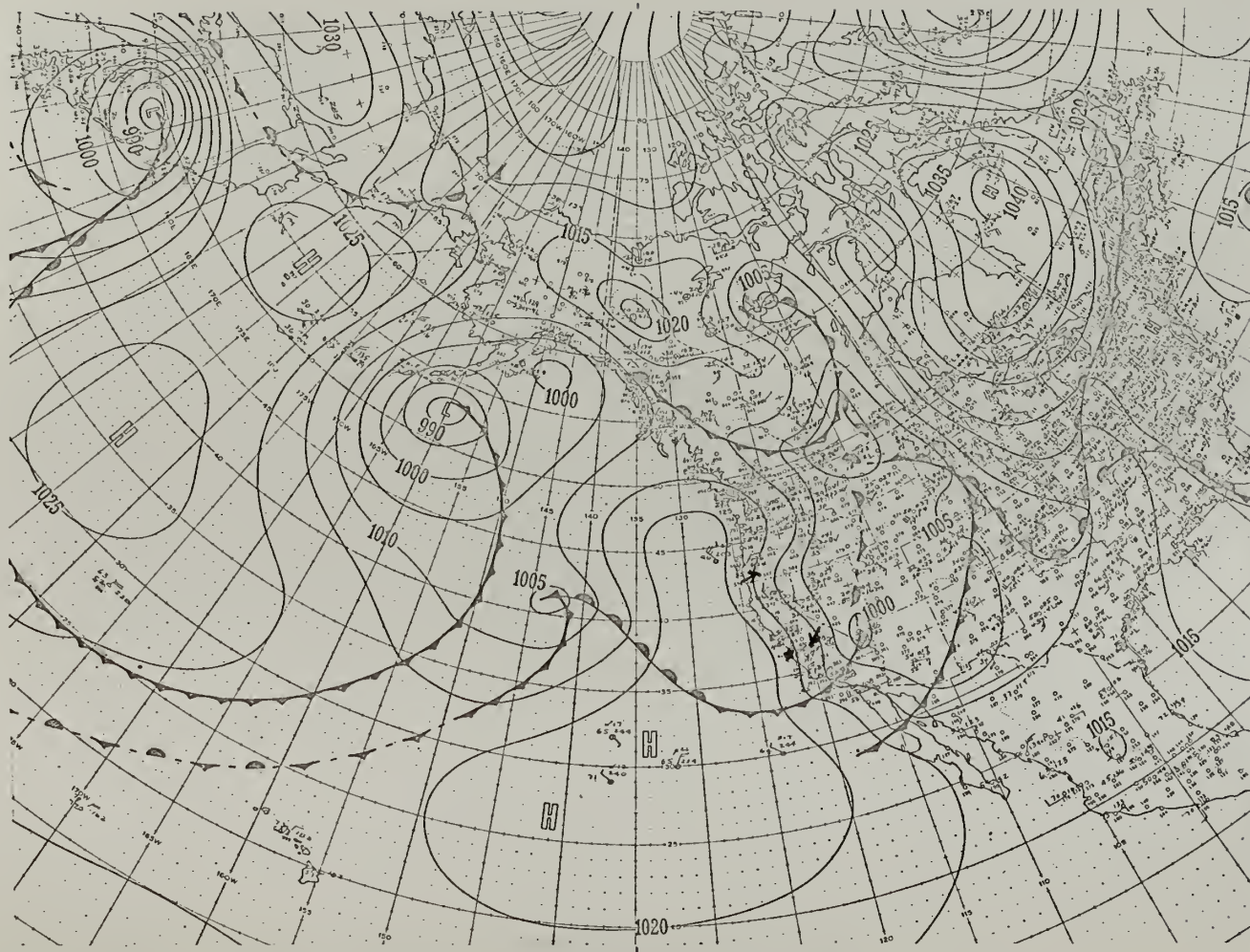


Fig. 20c. Surface Weather Map 1230Z 25 December 1942.

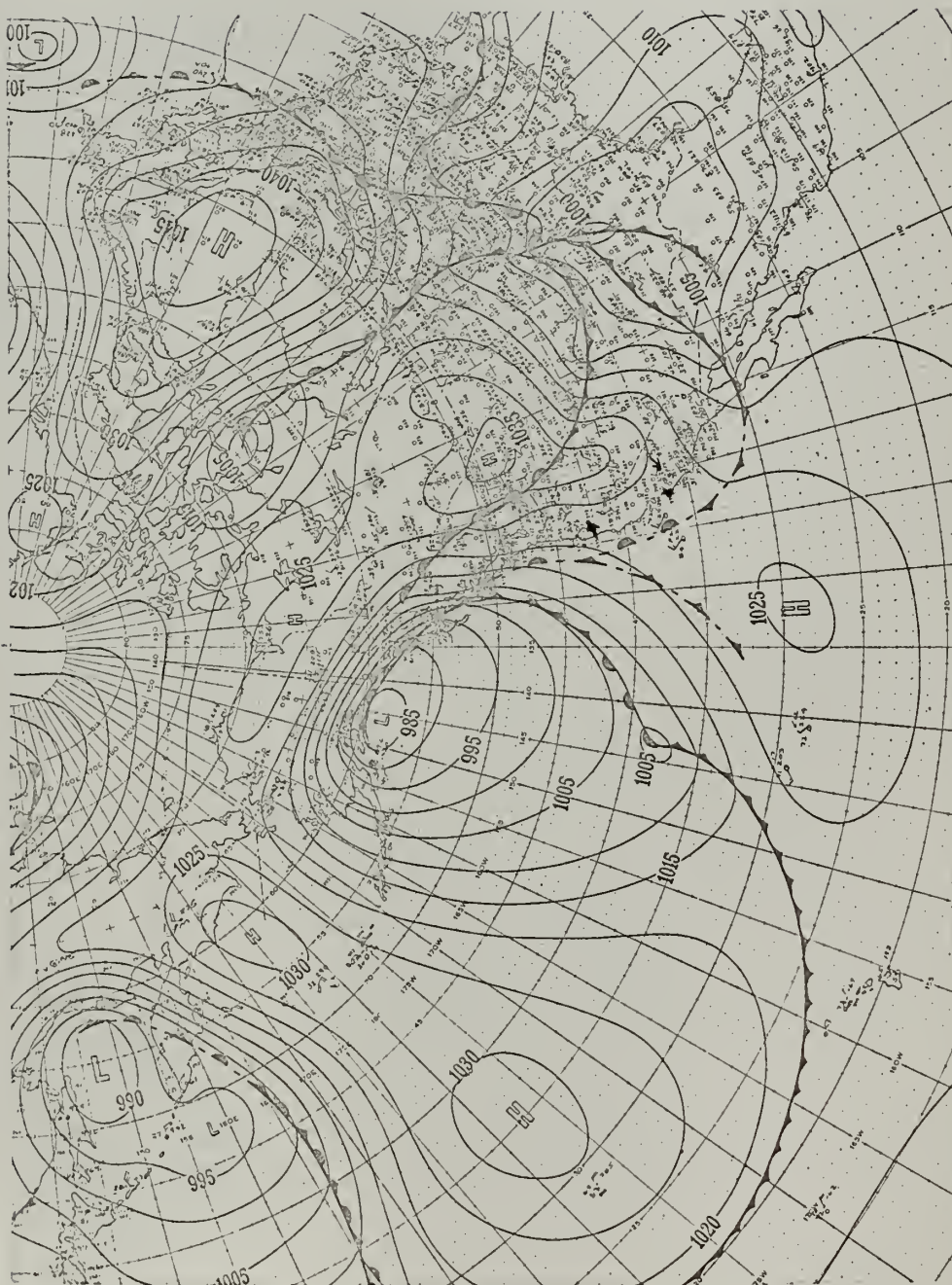


Fig. 20d. Surface Weather Map 1230Z 26 December 1942.





Fig. 21a. Surface Weather Map 1200Z 19 November 1931.

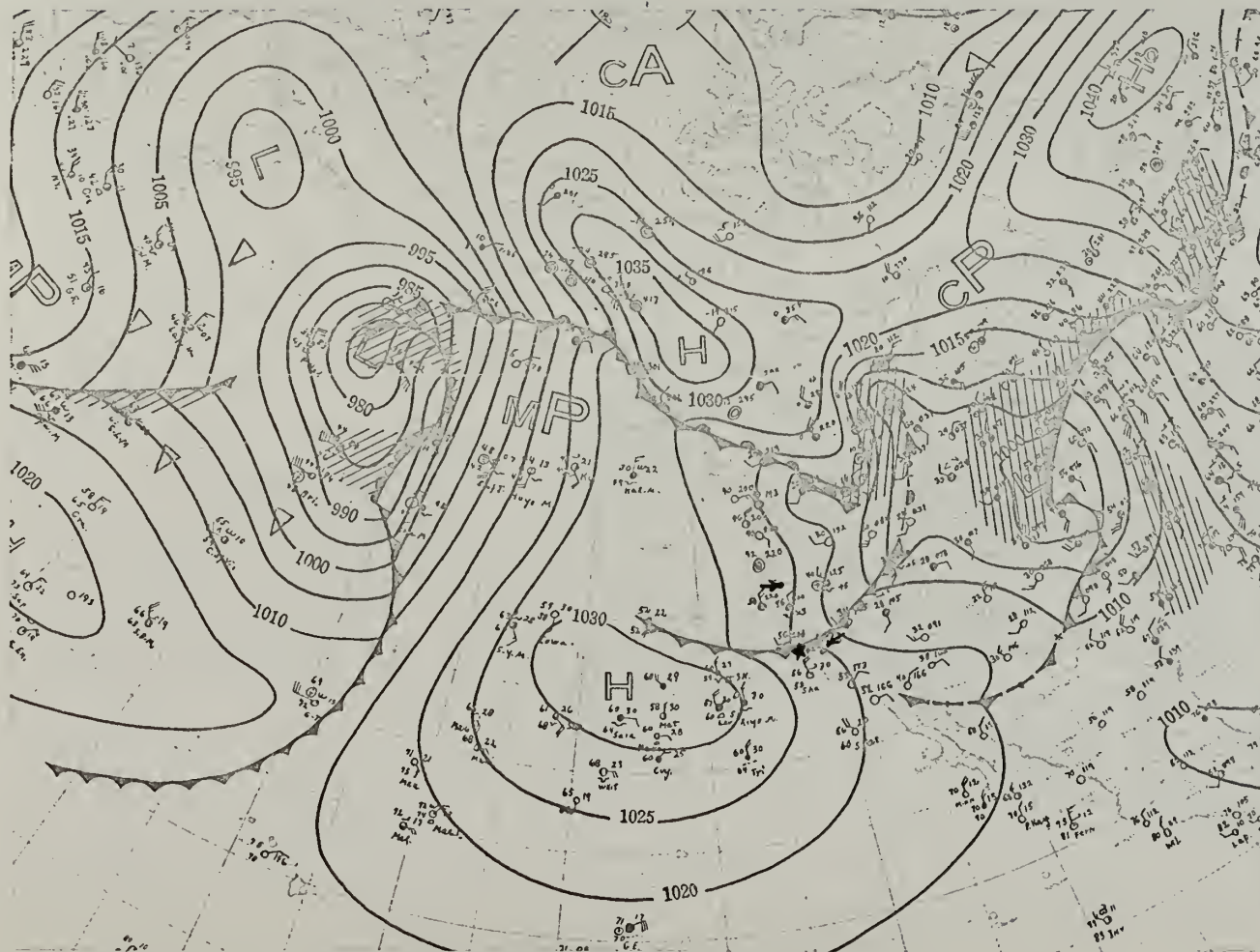


Fig. 21b. Surface Weather Map 1200Z 20 November 1931.



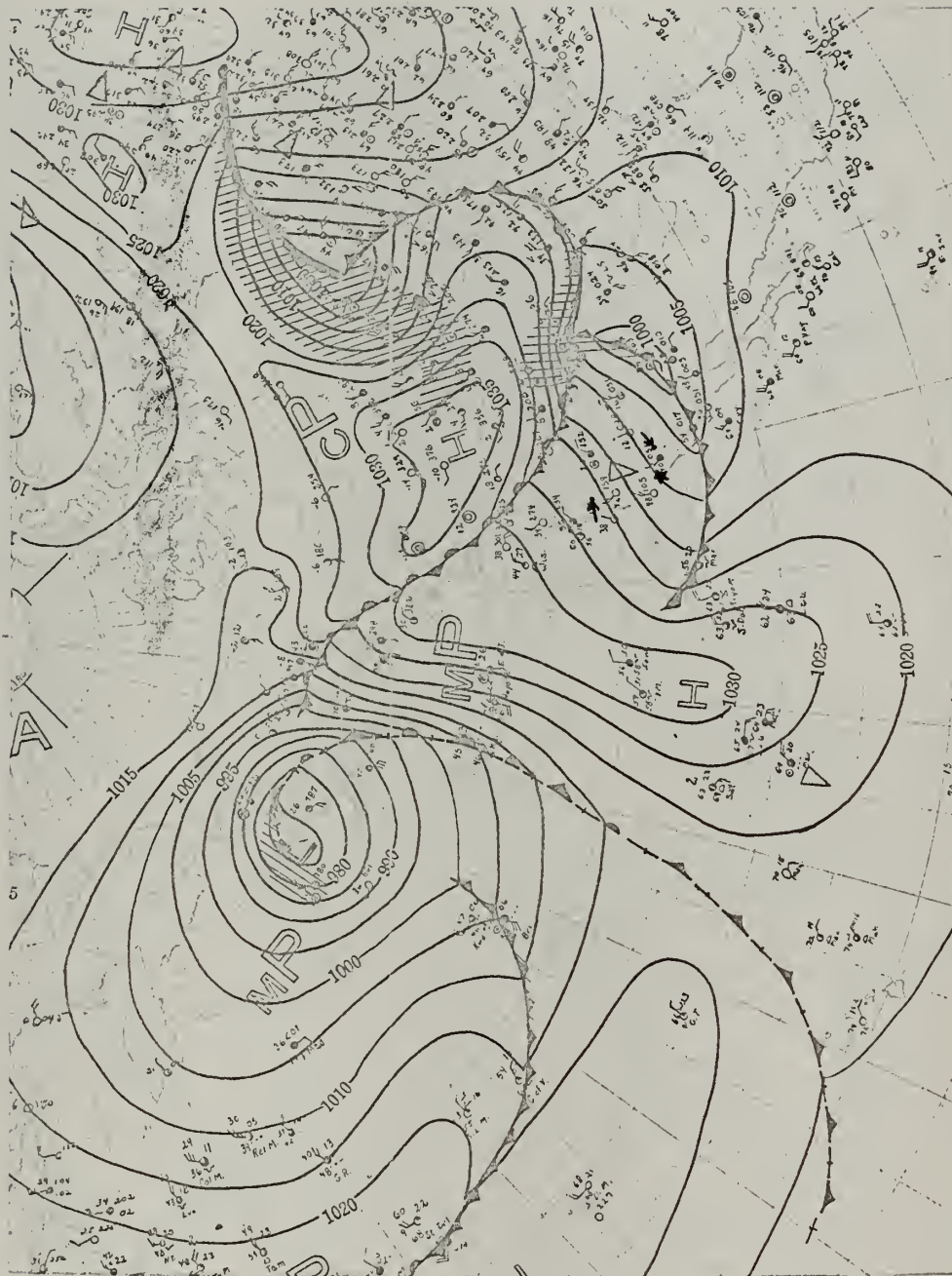


Fig. 21c. Surface Weather Map 1200Z 21 November 1931.

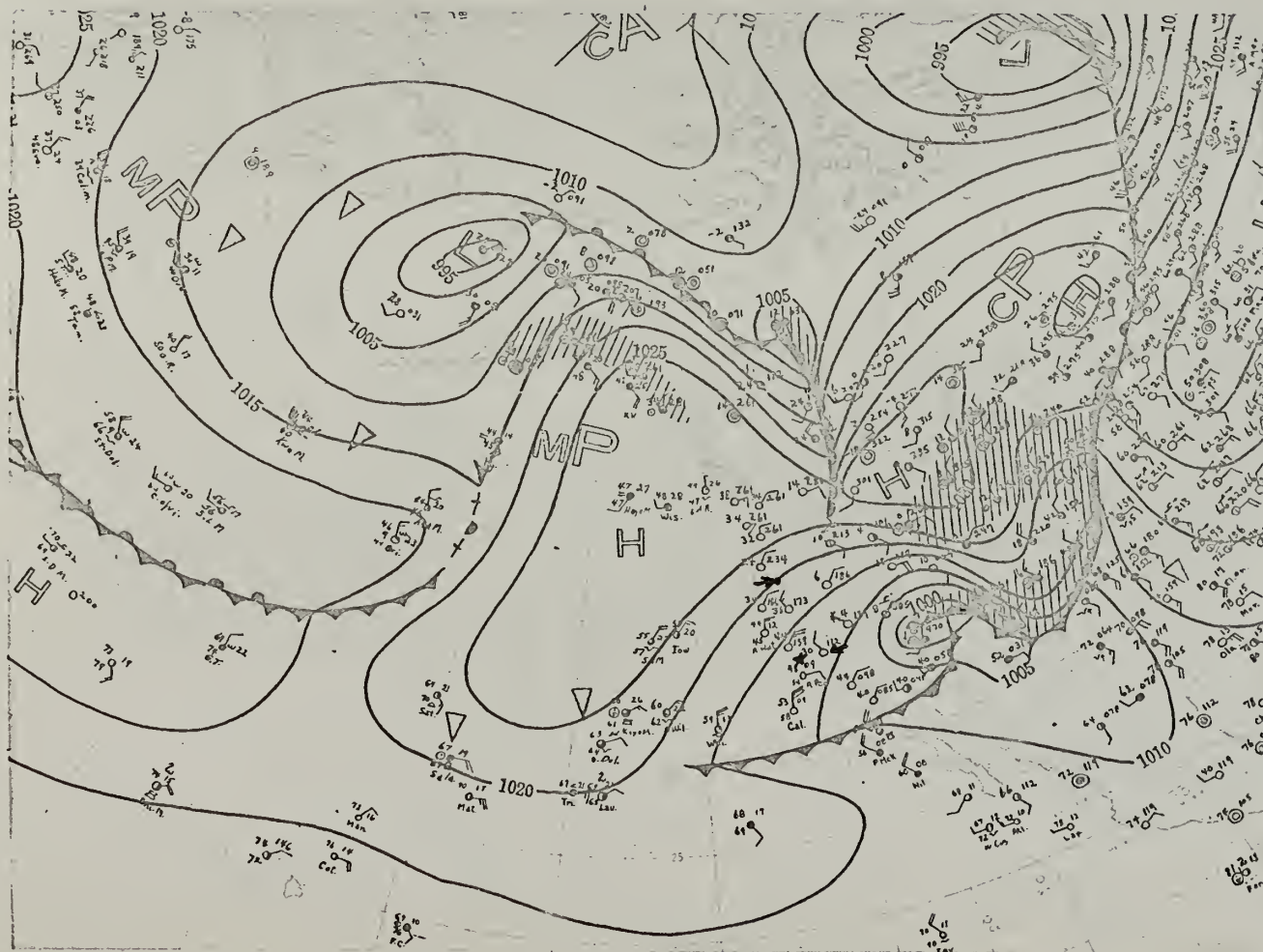


Fig. 21d. Surface Weather Map 1200Z 22 November 1931.

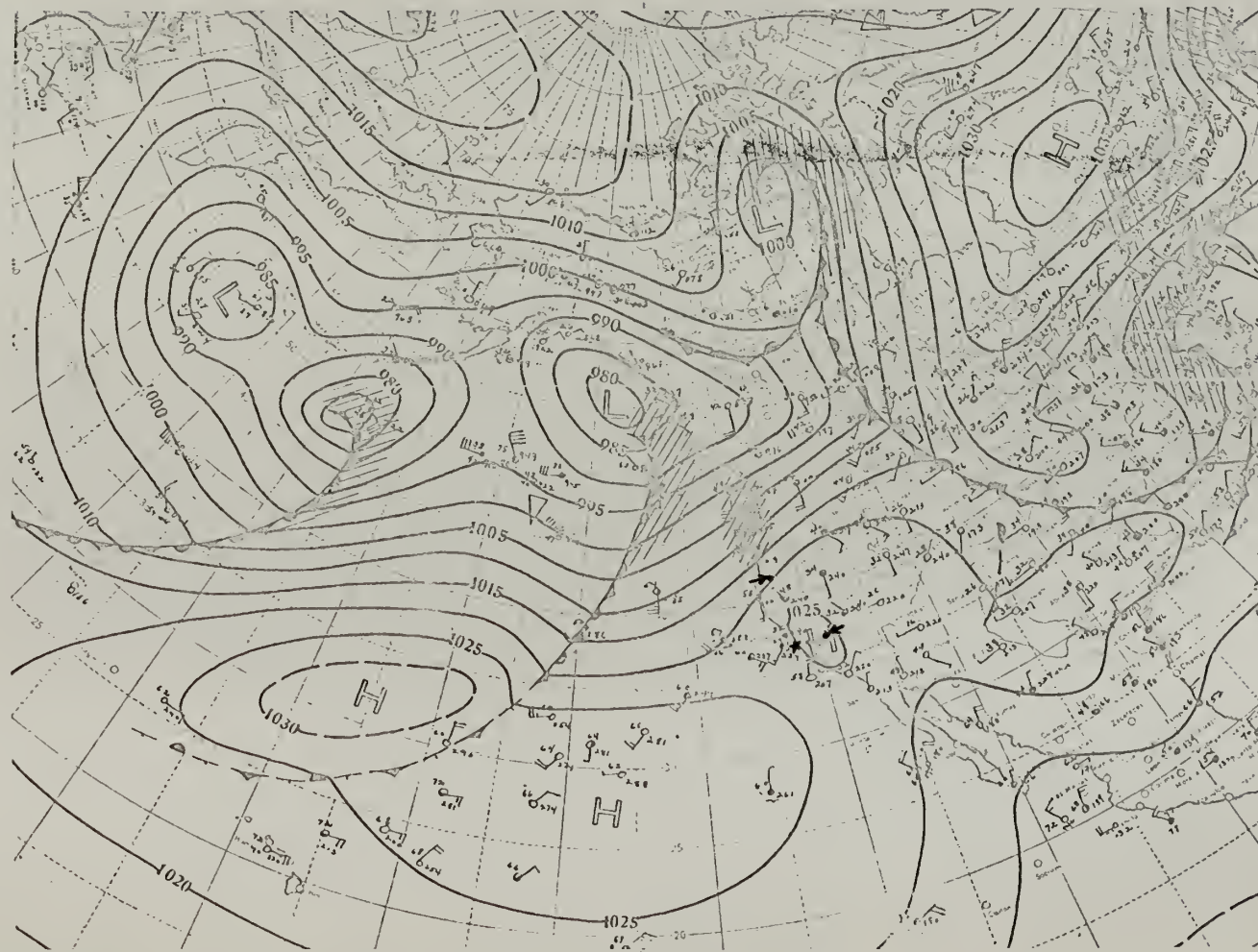


Fig. 22a. Surface Weather Map 1200Z 18 February 1931.



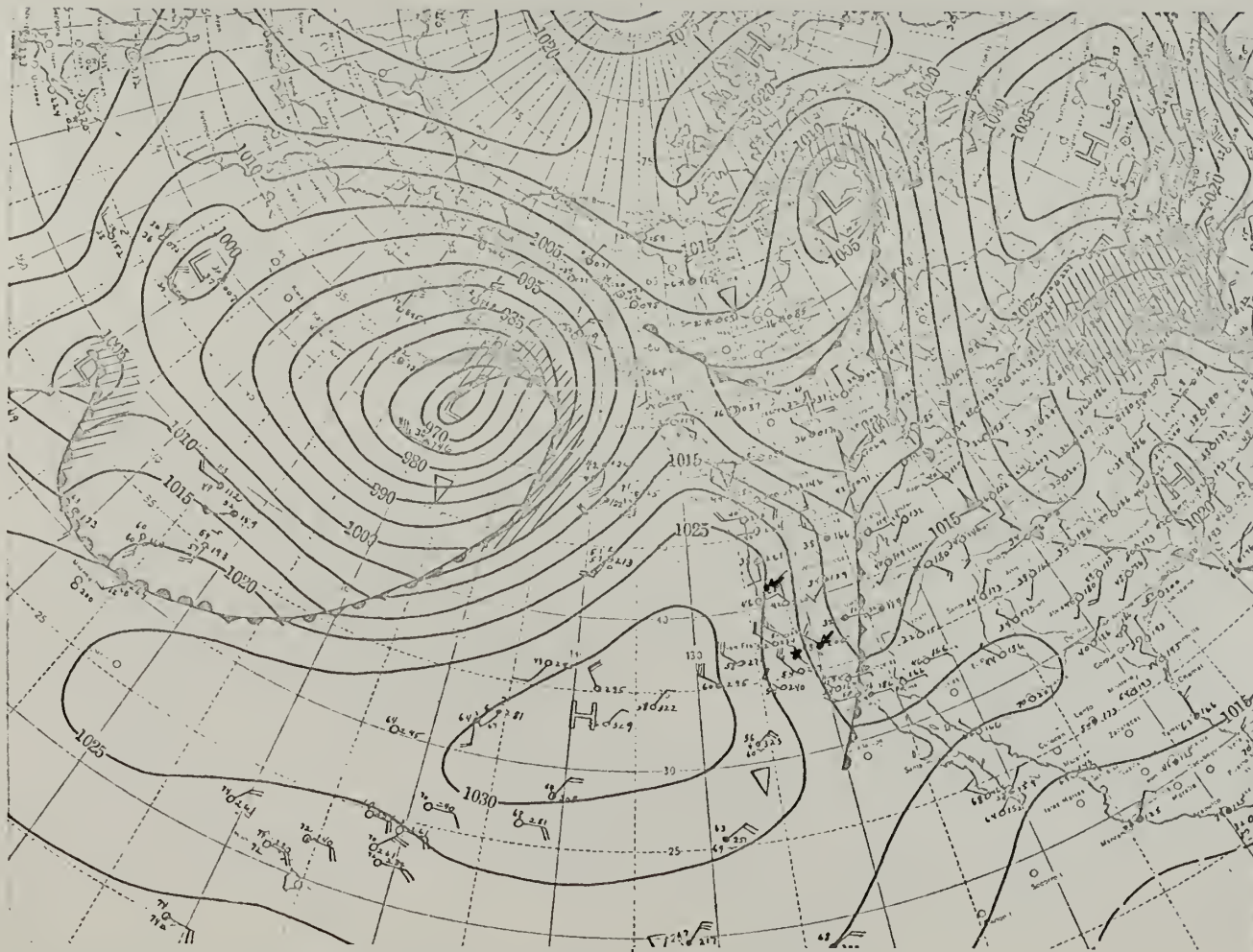


Fig. 22b. Surface Weather Map 1200Z 19 February 1931.





Fig. 22c. Surface Weather Map 1200Z 20 February 1931.



Fig. 22d. Surface Weather Map 1200Z 21 February 1931.

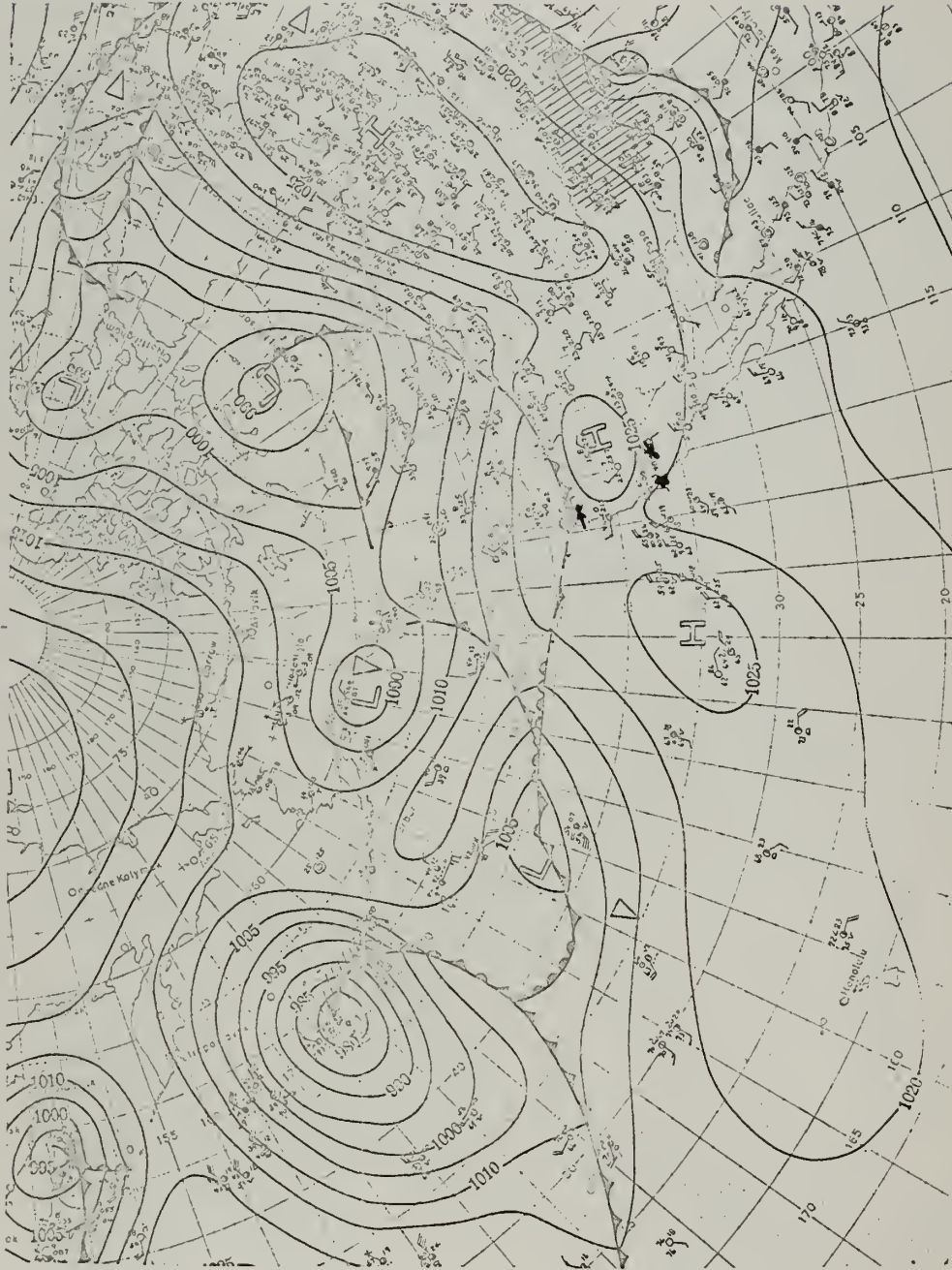


Fig. 23a. Surface Weather Map 1200Z 28 November 1923.



Fig. 23b

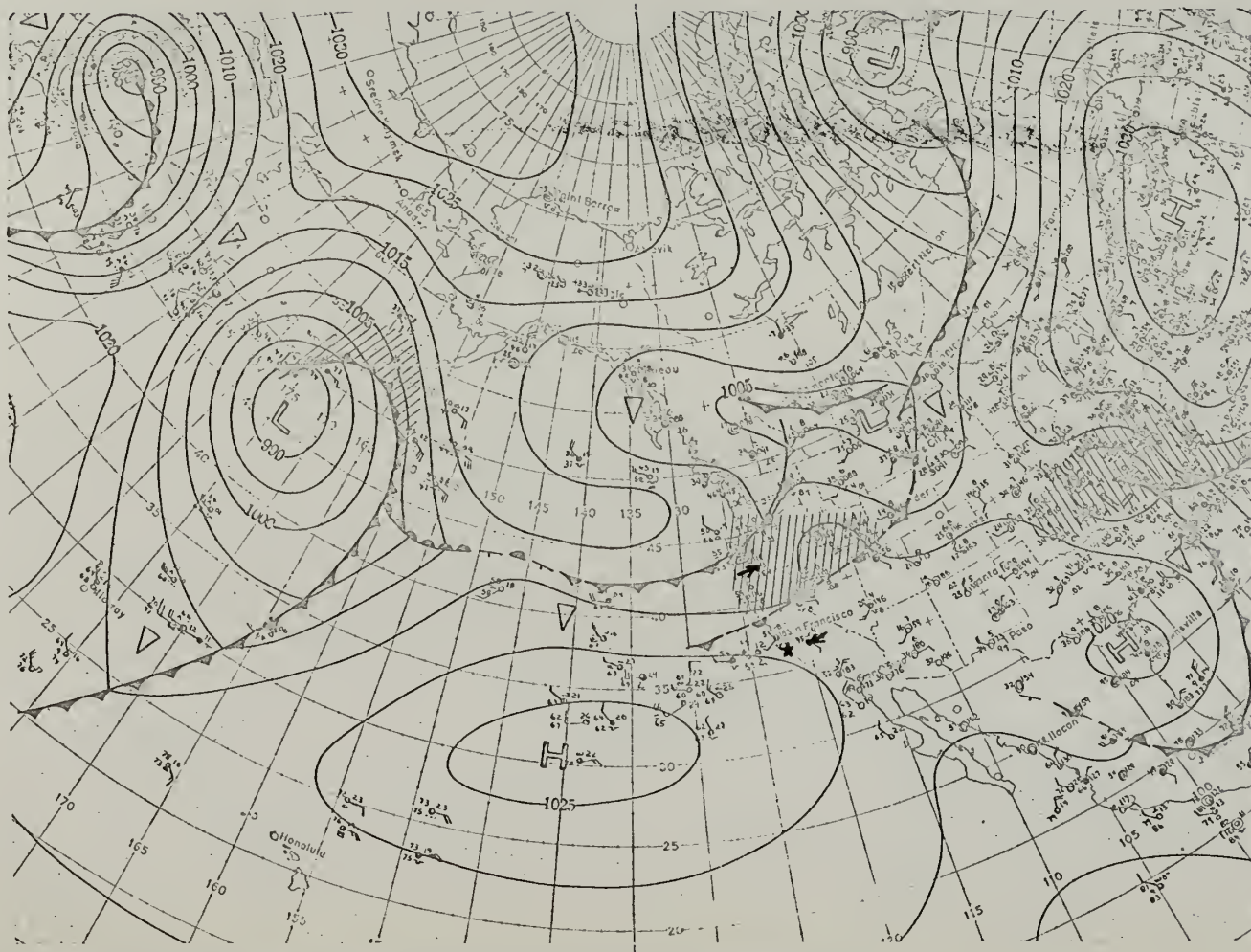
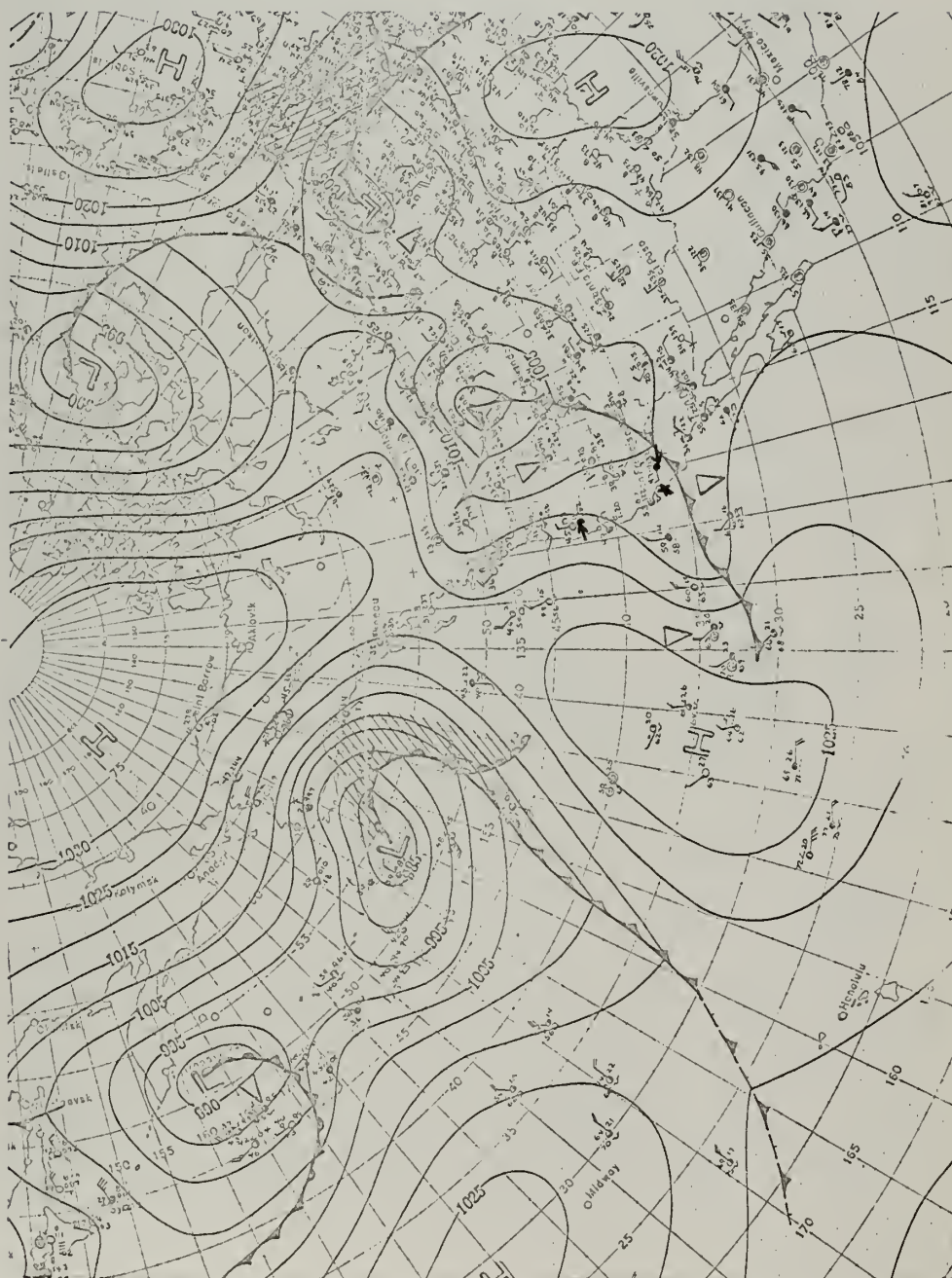


Fig. 23b. Surface Weather Map 1200Z 29 November 1923.





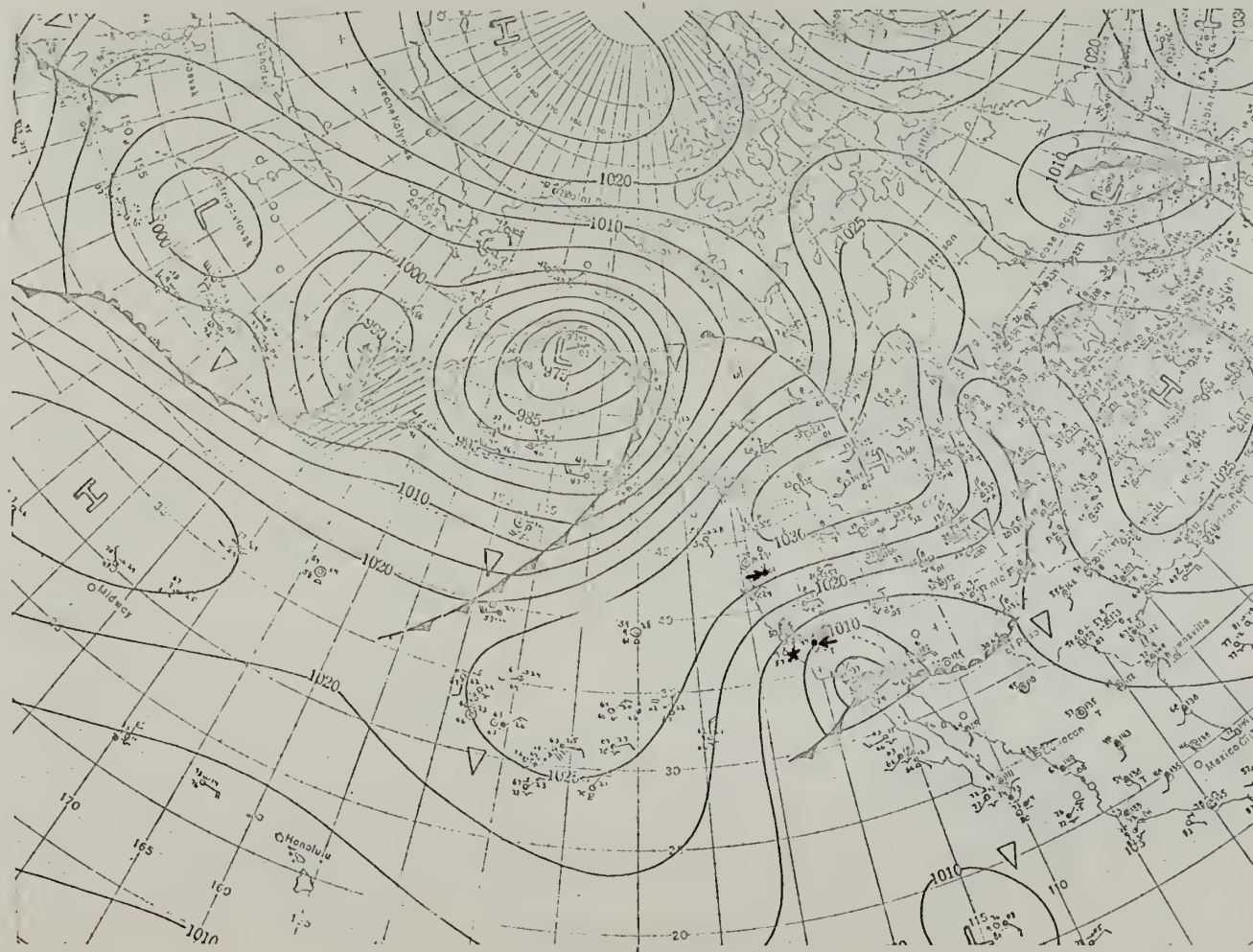


Fig. 23d. Surface Weather Map 1200Z 1 December 1923.

Fig. 23e. Surface Weather Map 1200Z 2 December 1923.





Fig. 24a. Surface Weather Map 1200Z 25 November 1919.



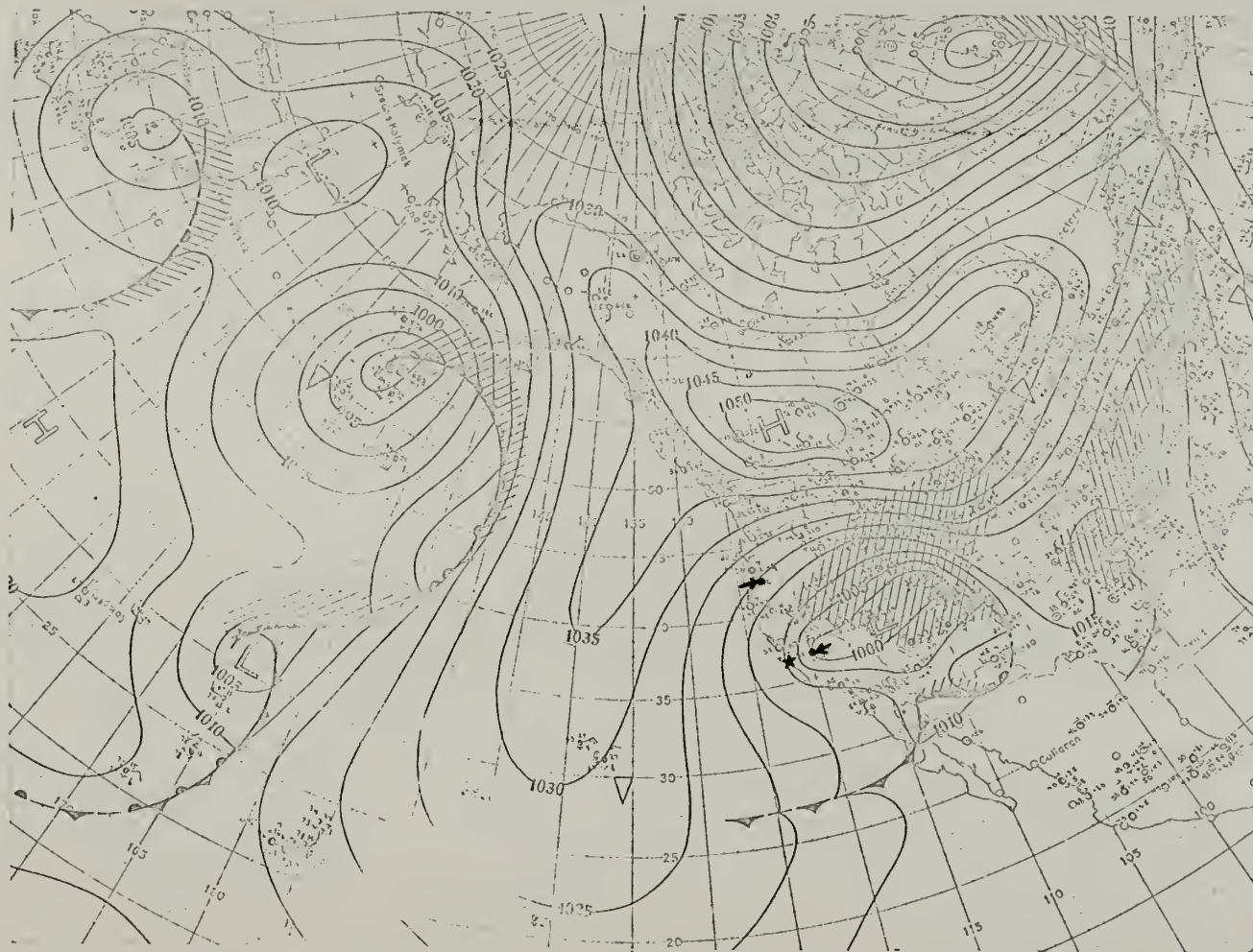


Fig. 24b. Surface Weather Map 1200Z 26 November 1919.

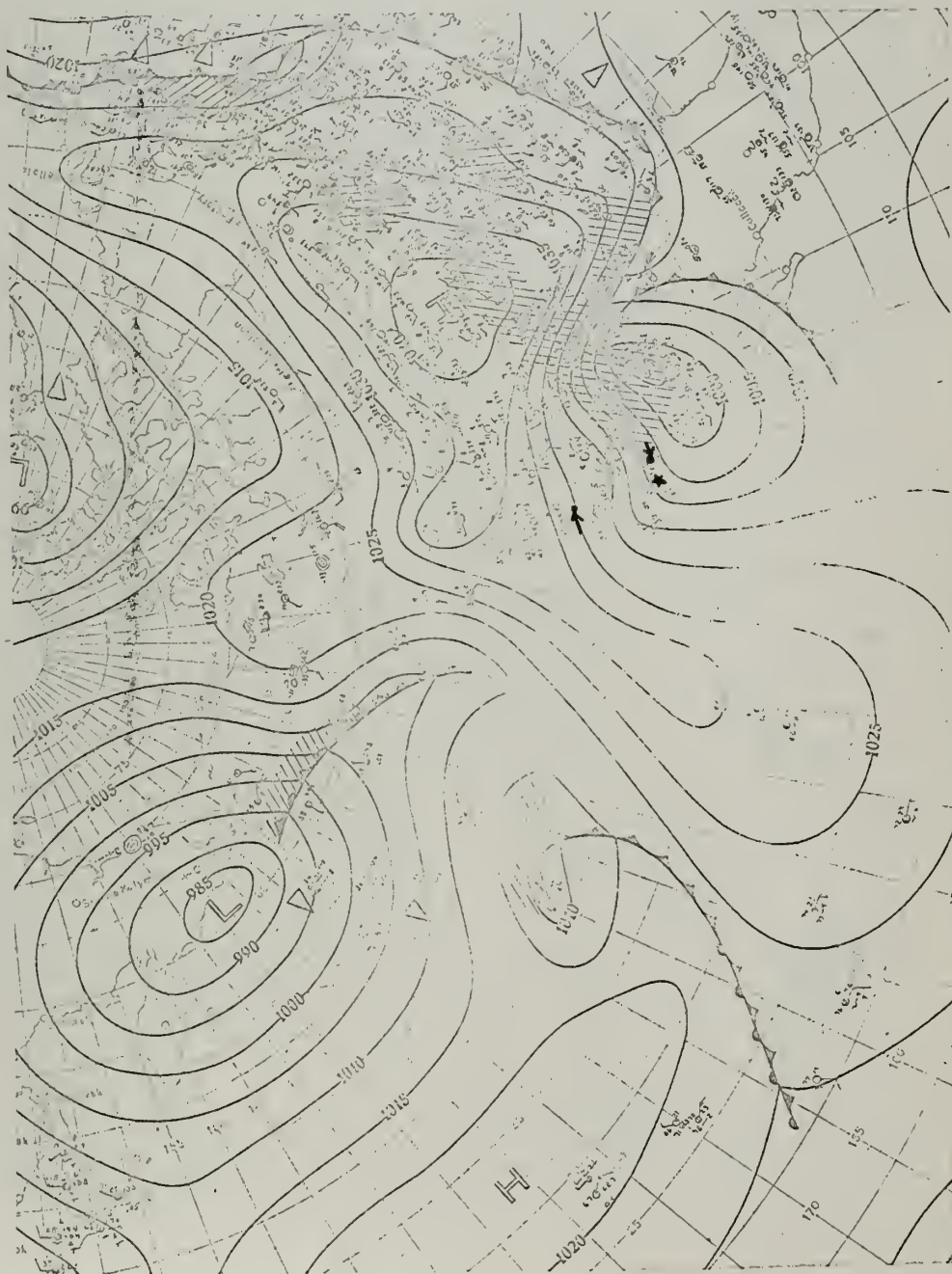


Fig. 24c. Surface Weather Map 1200Z 27 November 1919.

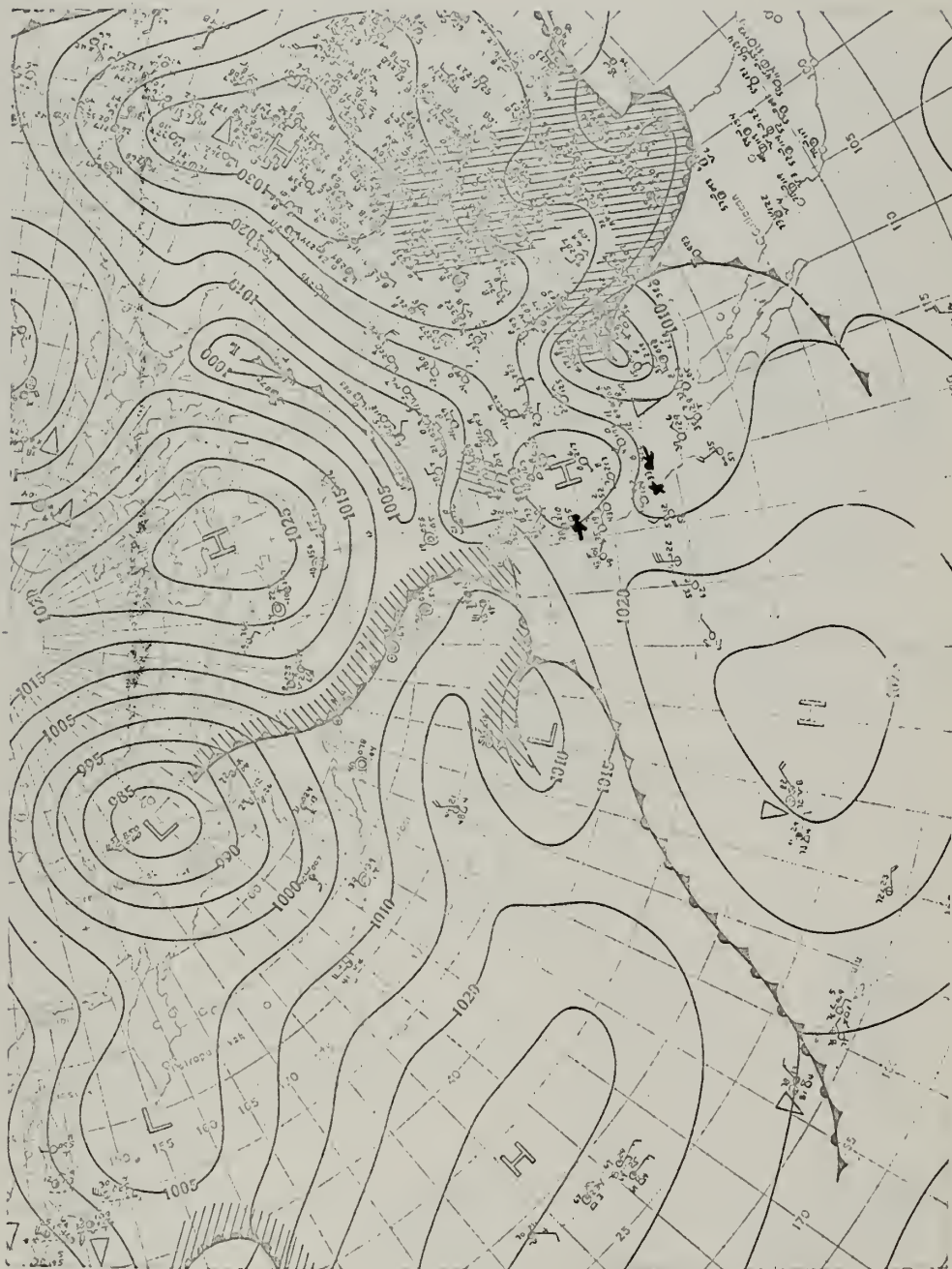


Fig. 24d. Surface Weather Map 1200Z 28 November 1919.



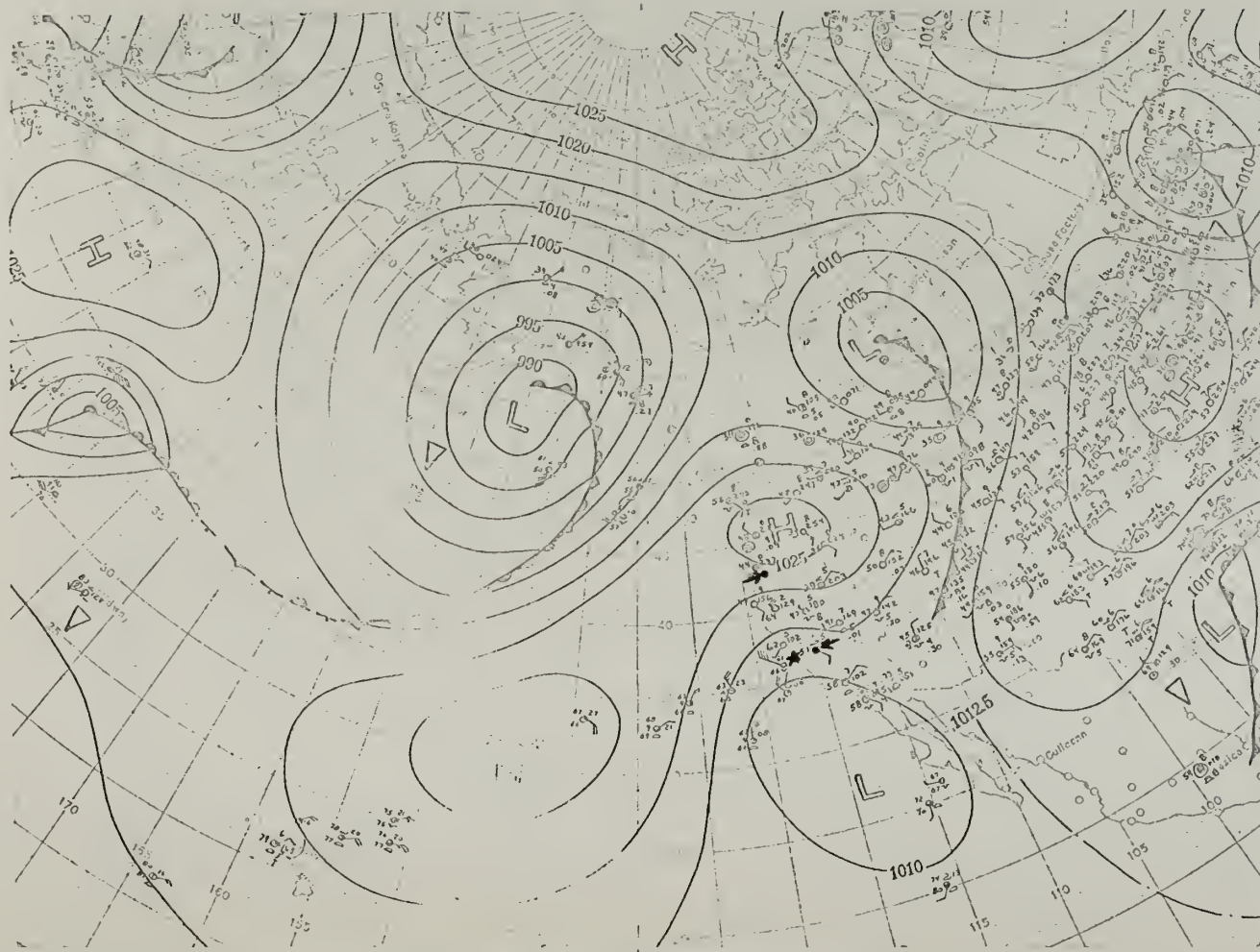


Fig. 25a. Surface Weather Map 1200Z 2 October 1912.



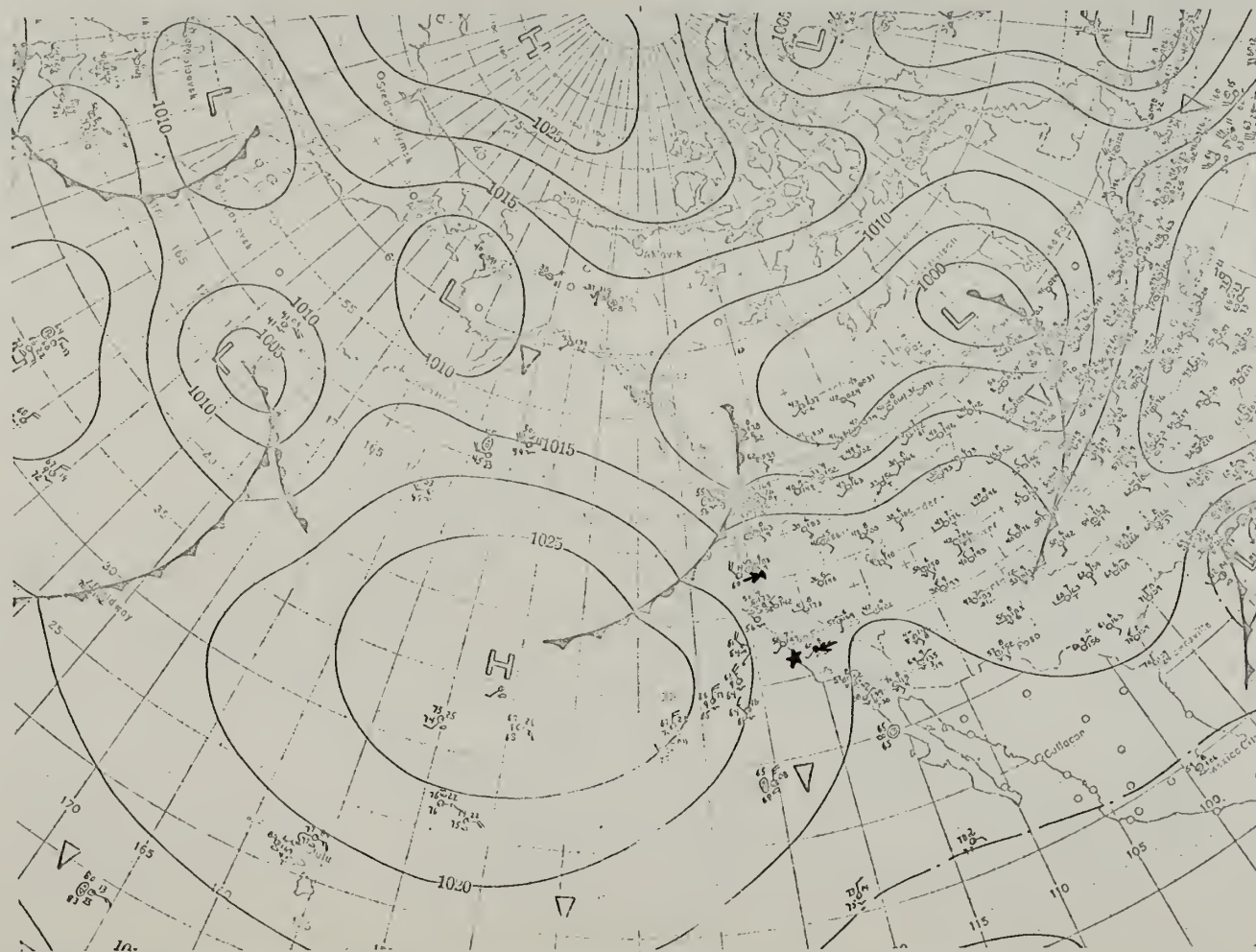


Fig. 25b. Surface Weather Map 1200Z 3 October 1912.



Fig. 25c. Surface Weather Map 1200Z 4 October 1912 (Storm Map).



Fig. 25d. Surface Weather Map 1200Z 5 October 1912.

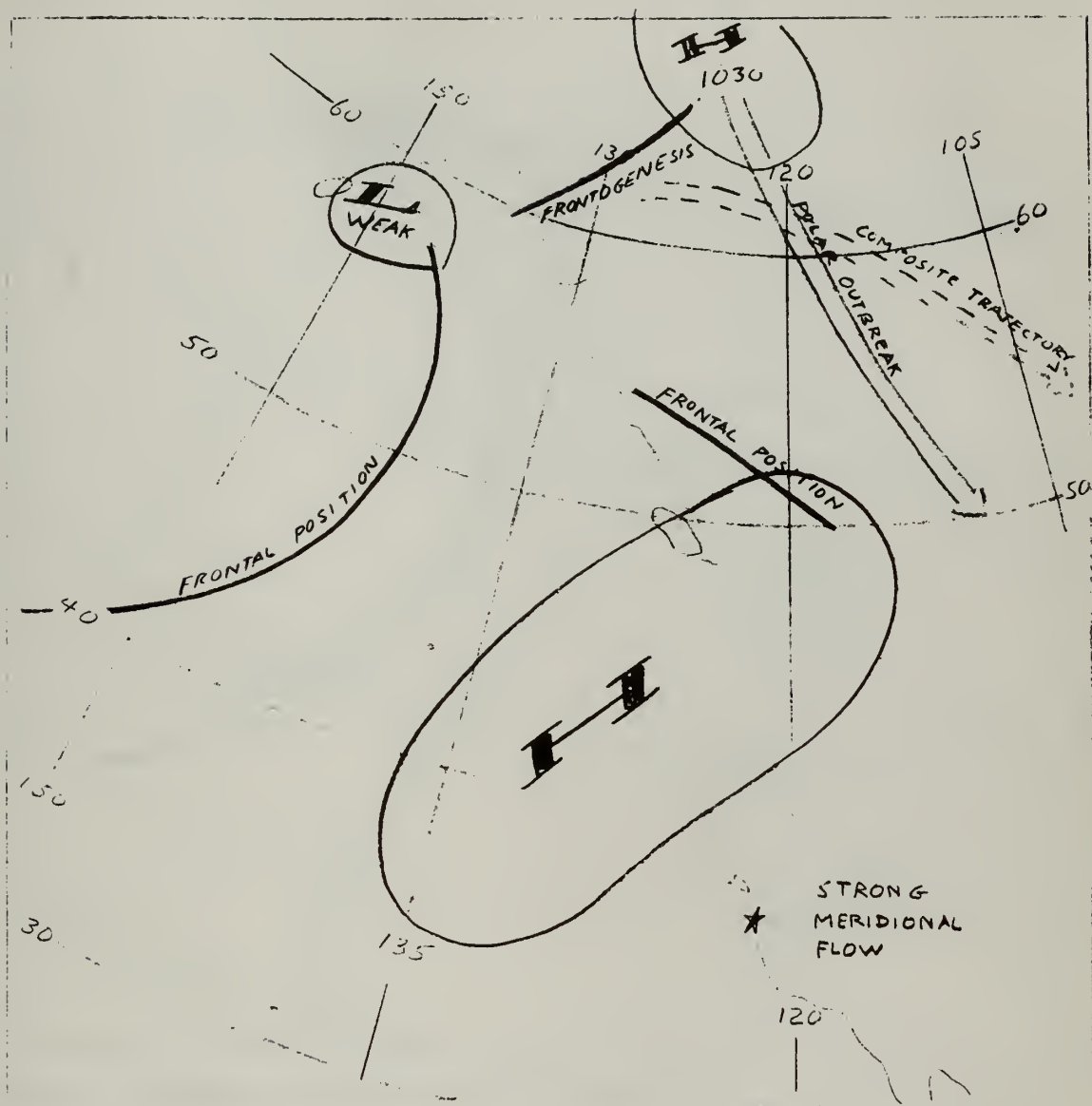


Fig. 26. Schematic diagram of North American Zone 3 Weather Type B<sub>Nc</sub>



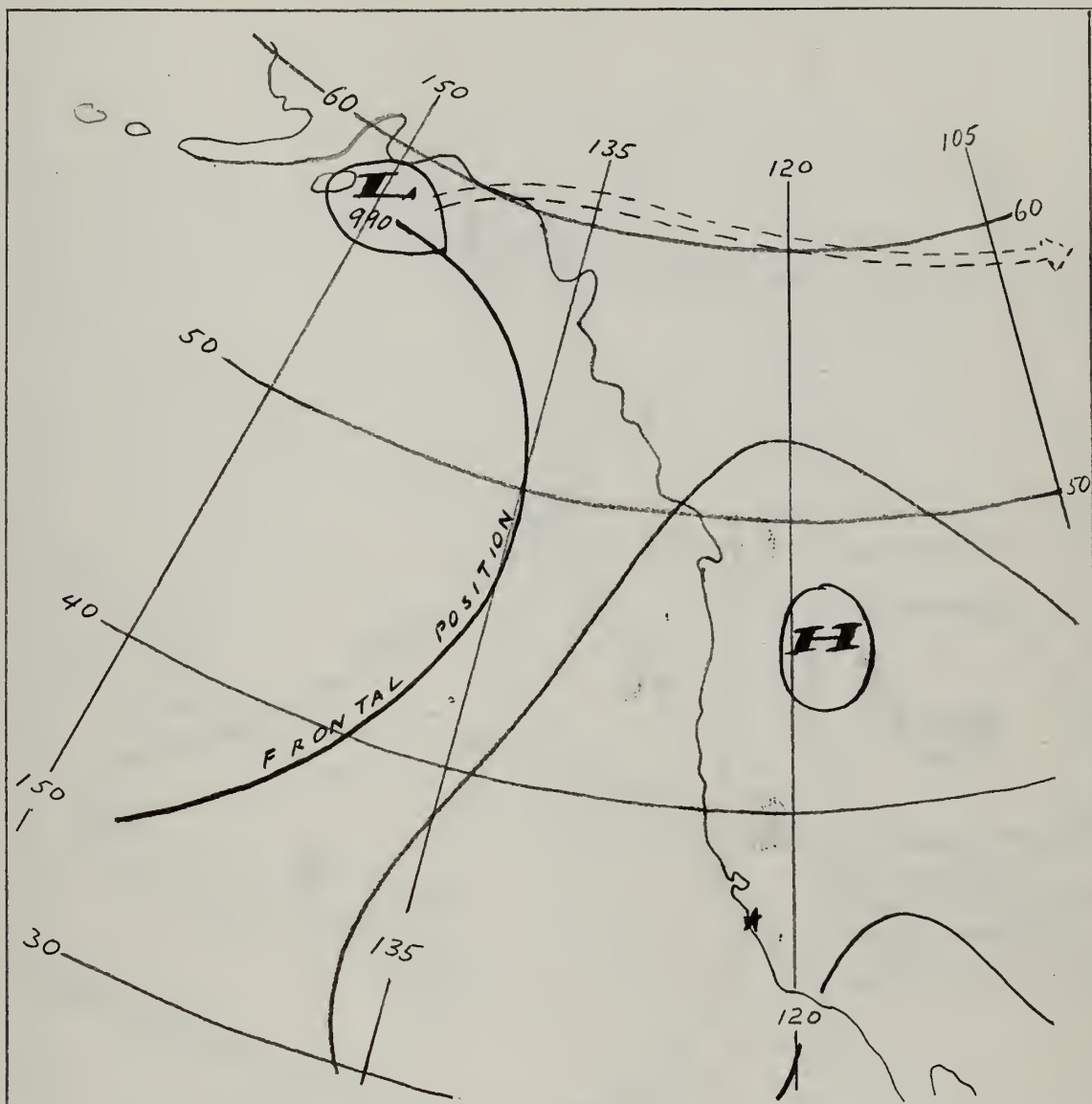


Fig. 27. Schematic diagram of North American Zone 3 Weather Type  $B_{Na}$

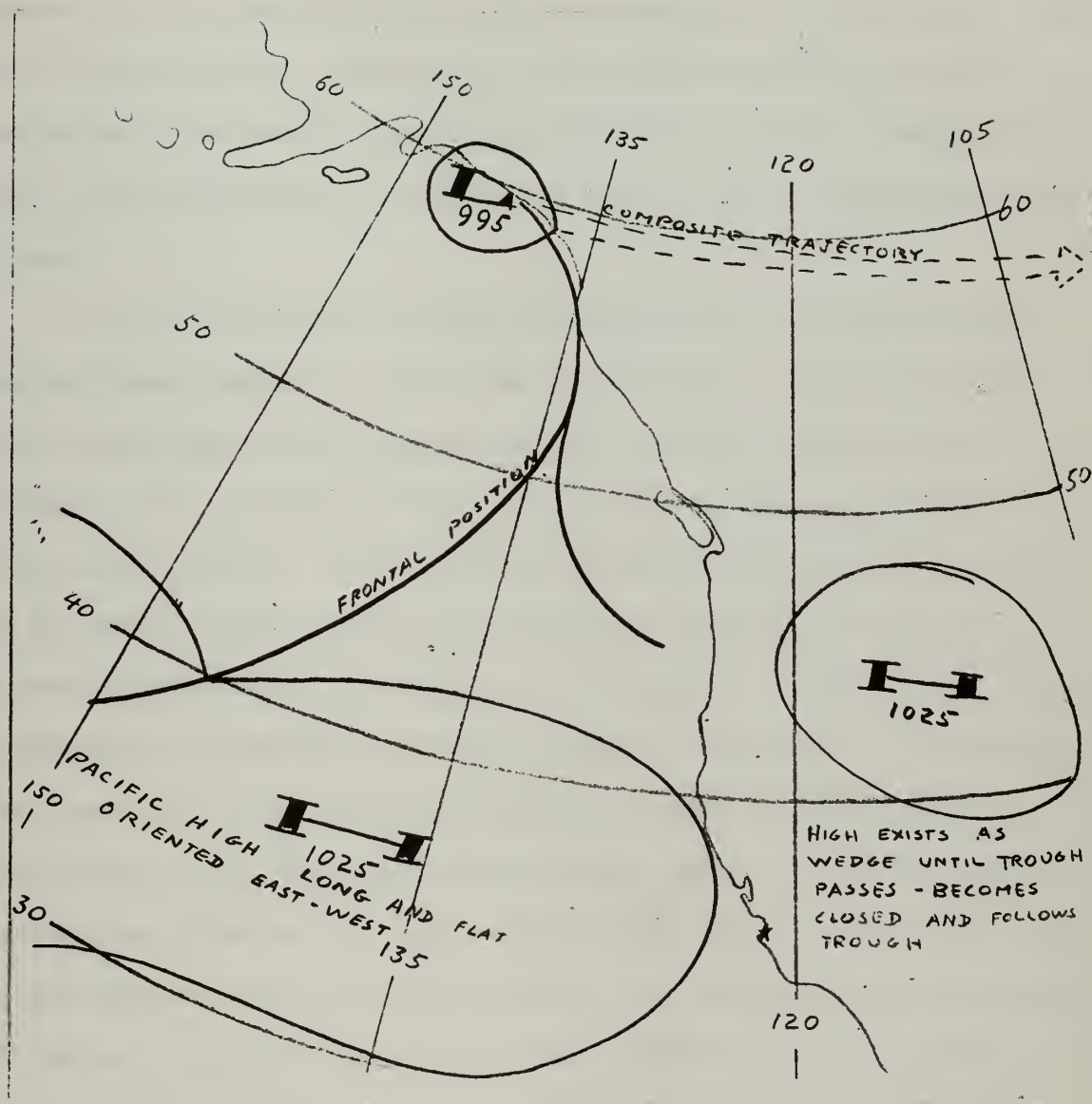


Fig. 28. Schematic diagram of North American Zone 3 Weather Type B.

## 7. Conclusion.

The first two purposes of the study, to document important storms and to describe the associated synoptic conditions, have been met. Only very limited success, however, was achieved with the third purpose, to determine if the synoptic conditions associated with the damaging storms were sufficiently unique to enable the forecasting of such storms in the future.

It was determined that certain of the Elliot-CIT North American Weather Types prevailed at the time of the storms. In the case of the Open Ocean Storms the  $E_L$  type was present in four of the six cases studied, while in the Bay Wind Storm case the  $B_N$  type was present in every storm studied. Thus it may be stated that detection or forecast of one of the above weather types should at least be a warning to observers that careful examination of the synoptic conditions for the possibility of destructive waves and/or wind is warranted. Location of storm centers, storm tracks, and pressure gradients resembling those described in this paper may provide further indications of the danger of destructive phenomena. In the case of the Bay Wind Storms, it was even determined that the  $B_N$  weather type has to be accompanied by a low center in central or southern California before high winds can be expected at Monterey. However, in the time available for research on this paper, it was not possible to determine how often similar synoptic conditions have prevailed when no storms occurred. Without such data, no absolute conclusions can be made regarding the uniqueness of the weather patterns associated with damaging storms.

A study of this nature would be one of considerable interest as a continuation of this current paper. In particular, the author feels

that because of the comparatively well-defined synoptic conditions in the case of the Bay Wind Storms, further pursuit of an objective technique similar to the Santa Ana wind forecast for the Bay Wind Storm could be very fruitful. With the possibility of damages running as high as one million dollars in a single storm, as in December 1943, a study which would yield forecasting tools for these storms, particularly the Bay Wind Storms, would be of great economic value to the area.



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## APPENDIX I

### CHRONOLOGICAL RECORD OF STORMS OVER THE PERIOD FROM 1910 TO 1960 AS REPORTED BY THE NEWSPAPERS

These brief descriptions are summaries of news accounts that appeared in the Monterey American, Monterey Daily Cypress, and the Monterey Peninsula Herald. The information given is exactly as it was in the newspapers with no attempt by the author to interpret or modify these descriptions. Where damage evaluations are not given in the descriptions, none were originally given in the papers. The reader may assume that where evaluations are presented in the text but not here, the writer has made his own estimate based upon the full account of the storm.

The classification of Open Ocean Storm (OOS) or Bay Wind Storm (BWS) has been made by the author. Surges are classified as Open Ocean Storms although no storm may have been in the vicinity at the time and the actual origin of surges is unknown. Storms marked with asterisk were studied in this paper.

1910	21 Mar	OOS	Heavy storm off the coast. Mountainous seas but Monterey Harbor calm. No damage.
1910	23 Oct	OOS	Several fishing boats broke loose and went ashore during a period of heavy swell in the Harbor. No damage.
1910	22 Nov	BWS	Bay was very rough and surf was running high. No ships able to enter or leave port. No damage.
1911	13 Feb	OOS	Mountainous waves were reported along the beach north of Monterey. No damage.
1912	4 Oct	BWS*	Strong northwest wind and heavy swell. Several wharves damaged and boats beached. Heavy surf

reported.

1915	29-30 April	OOS*	Heavy surf and strong winds. Considerable wind and wave damage to structures and boats. \$35,000 damage.
1915	26 Nov	OOS	Large and powerful swells breaking over wharves. No damage.
1916	27 Jan	OOS*	Southwest gale. No damage in Monterey, but steamship pier at Moss Landing destroyed by tremendous swells.
1919	27-28 Nov	BWS*	Violent windstorm. Northeasterly winds broke many boats loose from moorings and destroyed a large portion of fishing fleet. \$150,000 damage.
1923	29 Nov -1 Dec	BWS*	Northeast gale swept 15 boats ashore. Heavy seas reported outside Harbor, but no wave damage at Monterey. Estimated \$20,000 loss.
1926	11-15 Feb	OOS*	Southerly gale winds and wave damage all along the California coast but Monterey Harbor not hit. Carmel Beach under water and huge surf reported. Pier damaged at Moss Landing.
1926	25 Oct	OOS	Heavy swells running into Bay. Surf breaking over the old Del Monte Hotel wharf and onto boardwalk. No damage.
1926	8-9 Dec	BWS	Heavy swells washed one boat ashore and nearly swamped several lighters. Strong winds but no local storm. No significant damage.
1927	14-16 Feb	OOS	At the time was reported to be the most violent storm in the history of the Pacific Coast. Gale

winds, torrential rain, and heavy surf reported.

No damage to Harbor by wind or waves.

1927	4 Oct	OOS	Huge breakers reported all along central California coast. No local storm and no damage.
1928	23-28 March	OOS	Northwest winds, rain, heavy seas, plus a simultaneous strong surge in Monterey Harbor. Three small boats blown ashore undamaged and pier slightly damaged by steamer unloading at time of surge.
1928	30 Dec	OOS	Powerful surges caused about \$3,000 damage to freighter attempting to moor. No storm in vicinity.
1930	13 Nov	BWS	Strong northwest gale. One large purse seiner adrift.
1931	20 Feb	BWS*	North winds of gale intensity. Several small boats wrecked. Heavy surf reported. \$6,000 loss.
1931	20-21 Nov	BWS*	Strong winds and heavy seas beached numerous small boats.
1931	23-29 Dec	OOS*	Violent storm. Winds first from southwest, then northwest. Very heavy surf did most damage 26-27 December, breaking up roads, eroding coast, littering shoreline, and damaging piers and shoreline structures. \$50,000 damage.
1932	20-21 Dec	OOS	Rainstorm with strong winds from the northwest. Very rough on Bay and waves breaking over breakwater under construction. No damage.
1935	19 Dec	OOS	Very heavy surf. No local storm and no damage.
1937	10-11 Dec	OOS	Southwest winds and rain. One boat beached at Still-water Cove.



1939	10 Dec	BWS	Heavy rains and northerly winds with high waves. No damage.
1940	8 Jan	OOS	High waves breaking over sand bar at Carmel River mouth and completely over rocks at Point Lobos. No damage.
1941	11-13 Feb	OOS	Large waves in Bay and surge in Harbor. Two fishing boats broken loose. No significant damage.
1942	24-25 Dec	BWS*	North winds and high surf beached four purse seiners, with losses at \$80,000.
1943	22 Jan	OOS	Southwest wind estimated up to 70 mph. High surf reported but no wave damage. (There was considerable damage ashore in this storm.)
1943	8-9 Dec	BWS*	Very strong northeast winds wrecked forty fishing boats and piers and pilings in the Harbor. Damage placed at \$1,000,000. No other weather phenomena than strong winds.
1945	1-2 Feb	OOS	Southerly winds and torrential rains. Heavy seas but no damage reported.
1946	4 Mar	BWS	North winds up to 40 knots. Two large purse seiners driven ashore. Light damage only.
1947	28 Jan	BWS	Northerly gale-force winds; thunderstorm. 43-foot fishing boat capsized and beached; 80-foot section of sand dike holding dredging spoil washed out.
1947	4 Apr	BWS	Strong northerly winds with high surf in the Bay. No damage.
1948	23 Feb	BWS	Northwest winds up to 50 mph. Some boats beached. Damage light.

1949	2-3 Jan	BWS	High wind and seas. Several boats adrift and one lost.
1950	26 Oct	OOS*	Northerly gale winds accompanied by gigantic waves pounding the Peninsula. Damage to fishing fleet light but considerable shoreline erosion from the waves.
1951	1-4 Dec	BWS	Southeasterly and northerly winds with gusts to 53 mph. High surf but no damage.
1953	23 Feb	BWS*	Northeast gale winds up to 60 mph drove seven large fishing boats ashore. Damage amounted to about \$500,000.
1960	9 Feb	OOS*	Southerly winds with gusts to 45 mph accompanied by gigantic waves. Severe coastal erosion, shoreline roads damaged and littered with boulders, pier destroyed, boats smashed and one life lost. Damage set at \$85,000.

Summary by month and by storm type:

<u>Month</u>	<u>No. of OOS</u>	<u>No. of BWS</u>	<u>Total</u>
July	0	0	0
August	0	0	0
September	0	0	0
October	4	1	5
November	1	5	6
December	5	5	10
January	3	2	5
February	6	3	9
March	2	1	3
April	1	1	2
May	0	0	0
June	<u>0</u>	<u>0</u>	<u>0</u>
	22	18	40

## APPENDIX II

### WORKSHEETS FOR HINDCASTING DEEP-WATER OCEAN WAVES PRODUCED BY OPEN OCEAN STORMS

Included in this appendix are the worksheets showing values obtained in hindcasting deep-water wave heights and periods for the Open Ocean Storms studied. Wind areas which were examined but were found not to yield high waves by hindcasting procedures are not shown.

An "F" appearing as a superscript on fetch length indicates that the particular fetch length is the limiting condition at the time. An "FA" appearing for any time indicates a fully arisen sea. The meaning of other symbols used is given below along with the corresponding units.

<u>Symbol</u>	<u>Meaning</u>	<u>Units</u>
$U$	Surface wind speed	knots
$F$	Fetch length	nautical miles
$t_d$	Duration of wind	hours
$H_F$	Significant wave height at end of fetch	feet
$T_F$	Significant wave period at end of fetch	seconds
$\psi$	Direction from which waves were moving	degrees true
$D$	Decay distance	nautical miles
$F_{\min}$	Minimum fetch length (SMB definition)	nautical miles
$H_D$	Significant wave height at end of decay	feet
$T_D$	Significant wave period at end of decay	seconds
travel time	Travel time of wave front from end of fetch to end of decay	hours



ETA	Estimated time of arrival
GMT	Greenwich Mean Time
PST	Pacific Standard Time (local time)

[illegible]

		February		1960		(continued)					
Wind Area		A		A decay map		C		C		C	
Date/Time		10/12		10/12		08/00		08/12		08/18	
U		30	30	30	30	15/20	20	20	23	23	23
F		420 <sup>F</sup>	320 <sup>F</sup>	220 <sup>F</sup>	120 <sup>F</sup>	300	350	350	240	150	150
$t_d$		31	25	19	12	FA/10	16	19/10	16	16	16
$H_F$		19	19	18	15	6.8	8.0	8.0	9.1	10.5	10.5
$T_F$		12.0	11.3	10.4	9.0	6.3	7.4	8.2	8.2	8.2	8.2
$\psi$		290	290	290	290	245	246	250	250	250	250
D		300	400	500	600	120	60	0	0	0	0
$F_{min}$		420	320	220	120	70	135	80	160	160	160
$H_D/H_F$		0.56	0.48	0.39	0.28	.43	.67	1.00	1.00	1.00	1.00
$H_D$		10.6	9.1	7.0	4.2	2.9	5.4	9.1	10.5	10.5	10.5
$T_D/T_F$		1.15	1.19	1.27	1.38	1.26	1.12	1.00	1.00	1.00	1.00
$T_D$		13.8	13.8	13.2	12.4	7.9	8.2	8.2	8.2	8.2	8.2
travel time		14.5	20.0	25.0	32.0	10.0	5.0	0.0	0.0	0.0	0.0
ETA (GMT)		11/0230	11/0800	11/1300	11/2000	08/1000	08/1100	08/1800	08/1800	08/1800	08/1800
ETA (local)		10/1830	11/0000	11/0500	11/1200	08/0200	08/0900	08/1000	08/1000	08/1600	08/1600





					1950	26-27	October	(cont.)						
Wind Area	Decay Map B B B				C	C	C	C	C	C	C	C		
Date/Time	27/0630	27/0630	27/0630		23/0030	23/0630	23/1230	23/1830	24/0030	24/0630	24/1230	24/1830		
U	30	30	30		25/85	40	35	25	28	30	25	25		
F	500 <sup>F</sup>	300 <sup>F</sup>	100 <sup>F</sup>		900	900	900 <sup>F</sup>	900 <sup>F</sup>	900 <sup>F</sup>	900	900	700 <sup>F</sup>		
t <sub>d</sub>	35	24	10.5		15/18.5	17.5/14.5	23.5/50	50/52	52.5/52	52/59	38/52	46		
H <sub>F</sub>	19.5	18.5	14		16.5	25	27.5	15 <sup>FA</sup>	18	19	15 <sup>FA</sup>	14.7		
T <sub>F</sub>	12.4	11.1	8.5		9.0	11.8	15.1	11.6 <sup>FA</sup>	12.9	11.5	11.6 <sup>FA</sup>	11.4		
Ψ	270	270	270		330	325	325	325	325	310	320	315		
D	400	600	800		1740	1560	1180	1100	1200	1380	1400	1200		
F <sub>min</sub>	500	300	100		80	190	900	875	900	340	875	700		
H <sub>D</sub> /H <sub>F</sub>	0.50	0.40	0.24		0.14	0.25	0.45	0.43	0.43	0.31	0.40	0.39		
H <sub>D</sub>	9.9	7.4	3.4		2.3	6.25	12.4	6.5	7.7	5.9	6.0	5.7		
T <sub>D</sub> /T <sub>F</sub>	1.16	1.26	1.40		1.51	1.41	1.20	1.18	1.19	1.30	1.21	1.20		
T <sub>D</sub>	14.4	14.0	11.9		13.6	16.8	18.1	13.7	15.7	15.0	14.0	13.7		
Travel time	19.0	28.0	44.5		87.0	60.5	43.0	52.5	50.0	60.0	66.0	58.0		
ETA (GMT)	28/0130	29/1030	29/0500		26/1530	25/1900	25/0730	25/2300	26/0230	26/1830	27/0630	27/0430		
ETA (PST)	27/1730	28/0230	28/2100		26/0730	25/1100	24/2330	25/1500	25/1830	26/1030	26/2230	26/2030		

[illegible]

					1931	23-29 December								
Wind Area		A	A	A	A	A	A	A	A		C	C	C	C
Date/Time		$\frac{17}{1200}$	$\frac{18}{0000}$	$\frac{18}{1200}$	$\frac{19}{0000}$	$\frac{19}{1200}$	$\frac{20}{0000}$	$\frac{20}{1200}$	$\frac{21}{00}$		$\frac{19}{1200}$	$\frac{20}{0000}$	$\frac{20}{1200}$	$\frac{21}{0000}$
U		$\frac{25}{37}$	37	37	28	19	24	24	30		30	37	44	37
F		350	500	500 <sup>F</sup>	550 <sup>F</sup>	600	650	700	1000		1200	830	500	500 <sup>F</sup>
t <sub>d</sub>		$\frac{30}{13}$	25	32	37	39	$\frac{39}{17}$	29	$\frac{35}{18}$		12	$\frac{18}{15.5}$	$\frac{21.5}{19}$	$\frac{23}{32}$
H <sub>F</sub>		21	27	28	17.5	8.5 <sup>FA</sup>	11.5	13	17		15	23	32	28
T <sub>F</sub>		10.7	13.1	14.0	11.9	8.9	8.6	10.0	10.3		9.1	11.3	13.6	14.0
ψ		310	305	300	305	310	300	290	290		305	305	305	300
D		1606	1500	1400	1250	1130	760	515	500		1850	1825	1800	1600
F <sub>min</sub>		150	370	500	550	520	170	340	210		120	190	280	500
H <sub>D</sub> /H <sub>F</sub>		0.19	0.30	0.36	0.35	0.35	0.29	0.44	0.35		0.25	0.21	0.26	0.34
H <sub>D</sub>		4.0	8.1	10.1	6.10	3.0	3.3	5.7	6.0		3.7	4.8	8.3	9.5
T <sub>D</sub> /T <sub>F</sub>		1.44	1.32	1.28	1.24	1.20	1.32	1.21	1.27		1.44	1.40	1.38	1.29
T <sub>D</sub>		15.4	17.3	17.9	14.8	10.7	11.4	12.1	13.1		13.1	15.8	18.8	18.1
Travel time		68	56	51	56	70	44	29	25		93	76	62.5	58
ETA (GMT)		$\frac{20}{0800}$	$\frac{20}{0800}$	$\frac{20}{1500}$	$\frac{21}{0800}$	$\frac{22}{1000}$	$\frac{21}{2000}$	$\frac{21}{17}$	$\frac{22}{01}$		$\frac{23}{0700}$	$\frac{23}{0400}$	$\frac{23}{0230}$	$\frac{23}{1000}$
ETA (PST)		$\frac{20}{0000}$	$\frac{20}{0000}$	$\frac{20}{0700}$	$\frac{20}{0000}$	$\frac{22}{0200}$	$\frac{21}{1200}$	$\frac{21}{09}$	$\frac{21}{17}$		$\frac{23}{0100}$	$\frac{22}{2000}$	$\frac{22}{1830}$	$\frac{23}{0200}$



									1931	23-29 December	(cont.)		
Wind Area	AC	AC	AC	AC	AC	Decay AC	AC						
Date/Time	21/1200	22/0000	22/1200	22/1200	22/1200	22/1200	22/1200	22/1200	22/1200	22/1200	22/1200	22/1200	22/1200
U	37	30	25	25	25	25	25	25	25	25	25	25	25
F	1500	1200	920	600 <sup>F</sup>	300 <sup>F</sup>	100 <sup>F</sup>							
t <sub>h</sub>	44	56/61	52	42	26	11.5							
H <sub>F</sub>	30.	20	15 <sup>FA</sup>	14.5	13.5	11.0							
T <sub>F</sub>	15.2	14.0	11.8	11.2	10.0	7.9							
ψ	295	300	305	305	305	305							
D	500	500	500	820	1120	1320							
F <sub>min</sub>	775	1200	870	600	300	100							
H <sub>0</sub> /H <sub>F</sub>	0.56	0.59	0.55	0.42	0.31	0.24							
H <sub>0</sub>	16.8	11.8	8.3	6.1	4.2	2.6							
T <sub>0</sub> /T <sub>F</sub>	1.18	1.11	1.12	1.19	1.32	1.42							
T <sub>D</sub>	17.9	15.5	13.0	13.3	13.2	11.2							
Travel Time	19.0	21.0	25.0	40.5	56.0	79.0							
ETA (GMT)	22/0700	22/0800	23/0900	24/0430	24/0800	25/1200							
ETA (PST)	21/2300	22/1300	23/0500	23/0300	24/1200	25/0900							



					1931	23-29	December	(cont.)			
Wind Area	D	D	D	D	D	D	D	D	D	D	D
Date/Time	25/1200	26/0000	26/1200	27/0000	27/1200	28/0000	28/1200	29/0000	29/1200	29/1200	29/1200
U	30	37	44	39	34	28	25	25	22	22	22
F	550 <sup>F</sup>	750	1000	750 <sup>F</sup>	525 <sup>F</sup>	560 <sup>F</sup>	600 <sup>F</sup>	700 <sup>F</sup>	900	500 <sup>F</sup>	300 <sup>F</sup>
td	37.5/37.5	43.5/22.5	28.5/21.5	27.5/42	31/34	36/39	40/42	46	52/46	38	27
H <sub>F</sub>	20	26	33.5	34	25	18	14.5	15.0	11.5 <sup>FA</sup>	11.0	11.0
T <sub>F</sub>	12.7	12.8	14.0	15.7	13.5	12.0	11.2	11.5	10.5 <sup>FA</sup>	10.1	9.3
ψ	278	275	275	270	270	270	270	270	270	270	270
D	450	740	475	400	340	320	300	400	600	1000	1200
F <sub>min</sub>	550	320	340	750	525	560	600	700	700	500	300
H <sub>0</sub> /H <sub>F</sub>	0.40	0.39	0.48	0.56	0.51	0.58	0.60	0.57	0.49	0.36	0.30
H <sub>0</sub>	8.0	10.1	16.0	19.0	14.4	10.5	8.7	8.5	5.6	4.0	3.3
T <sub>D</sub> /T <sub>F</sub>	1.24	1.28	1.29	1.13	1.15	1.13	1.12	1.12	1.15	1.22	1.28
T <sub>D</sub>	15.8	16.4	18.1	18.0	15.5	13.6	12.6	12.9	12.1	12.3	11.9
travel time	39.0	30.0	17.5	15.0	15.0	16.0	15.5	20.0	32.0	53.0	66.0
ETA (GMT)	27/0300	27/0600	27/0530	27/1500	28/0300	28/1600	29/0330	29/0800	30/0100	31/1900	01/0600
ETA (PST)	26/1900	26/2200	26/2130	27/0700	27/1900	28/0500	29/1430	29/1200	30/1300	31/0930	01/0200

	1931					23-29 December (cont.)													
Wind Area	E	E	E	E	E	$\leftarrow E$	$E^{decay}$	$E \rightarrow$											
Date/Time	$\frac{25}{1200}$	$\frac{26}{00}$	$\frac{26}{1200}$	$\frac{27}{0000}$	$\frac{27}{1200}$	$\frac{27}{1200}$	$\frac{27}{1200}$	$\frac{27}{1200}$											
U	20	23	25	30	35	35	35	35											
F	300	450	600	450	300 <sup>F</sup>	200 <sup>F</sup>	100 <sup>F</sup>	50 <sup>F</sup>											
$t_d$	12	$\frac{18}{15.5}$	21	$\frac{27}{18}$	$\frac{24}{14}$	16.5	19.0	7.0											
$H_F$	7.5	10.5	13	17	12.3	22.0	17.5	13.0											
$T_F$	6.9	8.2	9.5	10.3	11.7	11.1	9.5	7.5											
$\psi$	270	240	235	230	230	230	230	230											
D	0	0	0	0	0	100	200	250											
$F_{min}$	90	150	225	210	300	200	100	50											
$H_D/H_F$	1.00	1.00	1.00	1.00	1.00	0.65	0.44	0.32											
$H_D$	7.5	10.5	13.0	17.0	12.3	14.3	7.7	4.3											
$T_D/T_F$	1.00	1.00	1.00	1.00	1.00	1.14	1.27	1.37											
$T_D$	6.9	8.2	9.5	10.3	11.7	12.7	12.1	10.3											
travel time	0	0	0	0	0	5.0	11.0	16.0											
ETA (GMT)	$\frac{25}{1200}$	$\frac{26}{0000}$	$\frac{26}{1200}$	$\frac{27}{0000}$	$\frac{27}{1200}$	$\frac{27}{1700}$	$\frac{27}{2100}$	$\frac{28}{0400}$											
ETA (PST)	$\frac{25}{0400}$	$\frac{25}{1600}$	$\frac{26}{0600}$	$\frac{26}{1600}$	$\frac{27}{0600}$	$\frac{27}{0900}$	$\frac{27}{1300}$	$\frac{27}{2000}$											

[illegible]



						1916	27 January									
Wind Area		A	A	A	A	A	A	A	A	A	A	A	A	Decay Map	A	A
Date/Time		$\frac{23}{1200}$	$\frac{24}{0000}$	$\frac{24}{1200}$	$\frac{25}{0000}$	$\frac{25}{1200}$	$\frac{26}{0000}$	$\frac{26}{1200}$	$\frac{27}{0000}$	$\frac{27}{1200}$	$\frac{28}{0000}$	$\frac{28}{1200}$	$\frac{28}{1200}$	$\frac{28}{1200}$	$\frac{28}{1200}$	$\frac{28}{1200}$
U		$\frac{20}{30}$	25	20	25	30	25	20	30	38	25	25	25	25	25	25
F		570	600 <sup>F</sup>	600 <sup>F</sup>	700	800	700 <sup>F</sup>	600	725	850	400 <sup>F</sup>	350 <sup>F</sup>	250 <sup>F</sup>	150 <sup>F</sup>	50 <sup>F</sup>	
t <sub>d</sub>		$\frac{36}{185}$	$\frac{24.5}{42}$	$\frac{42}{42}$	$\frac{42}{18}$	$\frac{24}{17}$	$\frac{23}{46}$	$\frac{46}{42}$	$\frac{42}{19}$	$\frac{25}{16}$	$\frac{22}{82.5}$	29	23	15.5	7.0	
H <sub>F</sub>		17.5	14.5	9.5 <sup>FA</sup>	12.5	17	15	9.5 <sup>FA</sup>	17.5	24	14.2	14	13.2	12.0	8.7	
T <sub>F</sub>		10.4	11.2	9.3	9.1	10.1	11.5	9.3	10.5	11.7	10.6	10.4	9.7	8.7	6.7	
Ψ		320	320	320	315	310	310	310	290	270	290	290	290	290	290	
D		250	250	250	250	250	400	550	150	0	50	100	200	300	400	
F <sub>min</sub>		220	600	575	180	190	700	575	320	350	400	350	250	150	50	
H <sub>D</sub> /H <sub>F</sub>		0.50	0.62	0.61	0.46	0.48	0.57	0.46	0.58	1.00	0.84	0.70	0.55	0.40	0.33	
H <sub>D</sub>		8.75	9.0	5.8	5.7	8.2	8.6	4.4	10.2	24.0	11.8	9.8	7.8	4.8	2.9	
T <sub>D</sub> /T <sub>F</sub>		1.20	1.10	1.10	1.22	1.22	1.12	1.13	1.15	1.00	1.05	1.10	1.17	1.25	1.38	
T <sub>D</sub>		12.5	12.3	10.2	11.1	12.3	12.9	10.9	12.1	11.7	11.1	11.4	11.0	10.9	9.2	
Travel time		13.0	13.5	16.0	15.0	13.5	20.5	34.5	7.5	0	3.0	6.0	12.0	18.0	28.5	
ETA (GMT)		$\frac{24}{0100}$	$\frac{24}{1330}$	$\frac{25}{0400}$	$\frac{25}{1500}$	$\frac{26}{0130}$	$\frac{26}{2050}$	$\frac{27}{2230}$	$\frac{27}{0730}$	$\frac{27}{11200}$	$\frac{28}{0300}$	$\frac{28}{1800}$	$\frac{29}{0000}$	$\frac{29}{0600}$	$\frac{29}{1630}$	
ETA (PST)		$\frac{23}{1700}$	$\frac{24}{0530}$	$\frac{24}{2000}$	$\frac{25}{0700}$	$\frac{25}{1750}$	$\frac{26}{1230}$	$\frac{27}{1430}$	$\frac{26}{2550}$	$\frac{27}{0400}$	$\frac{27}{1900}$	$\frac{28}{1000}$	$\frac{28}{1600}$	$\frac{28}{2200}$	$\frac{29}{0830}$	



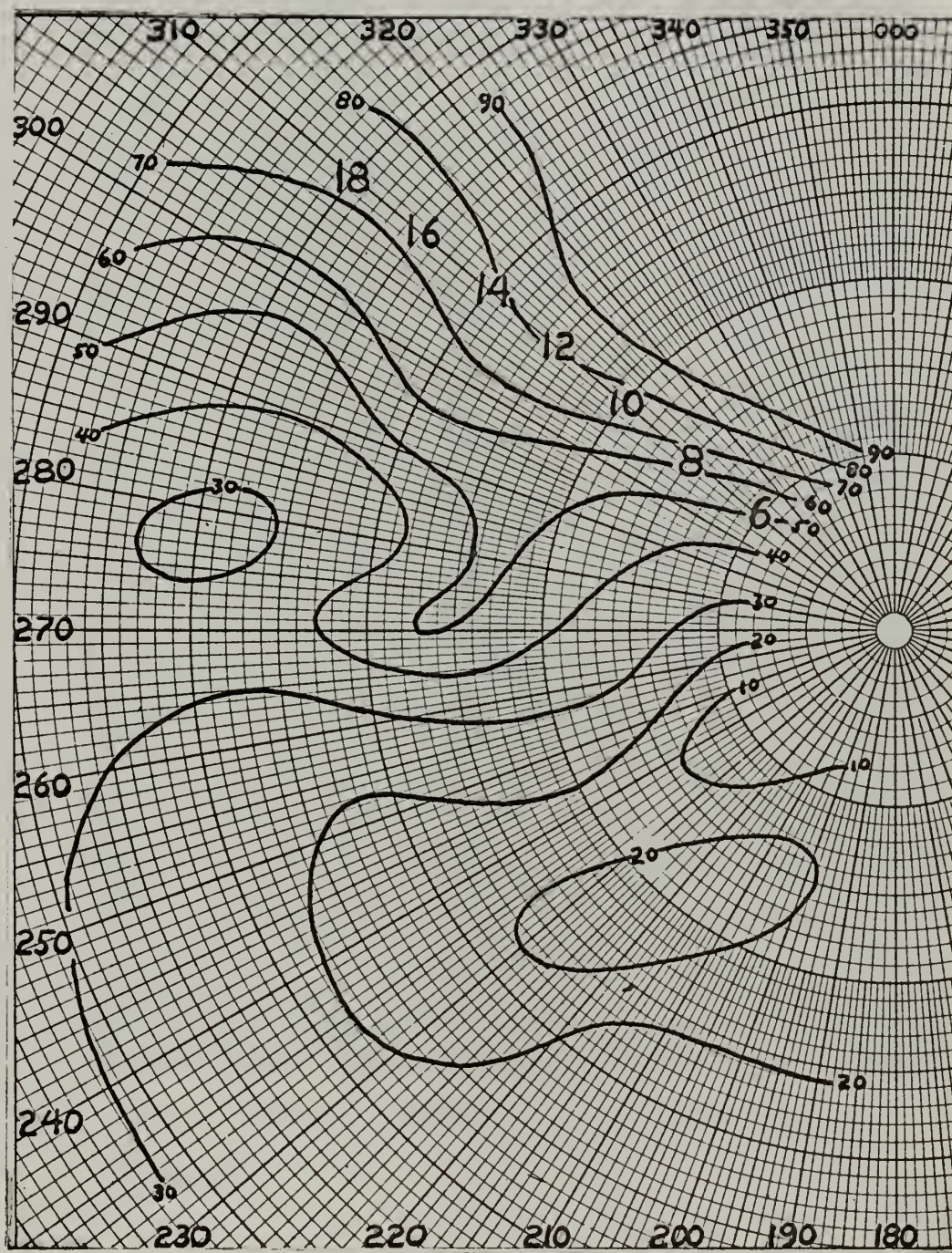


### APPENDIX III

#### CURVES OF REFRACTION COEFFICIENTS FOR MONTEREY HARBOR

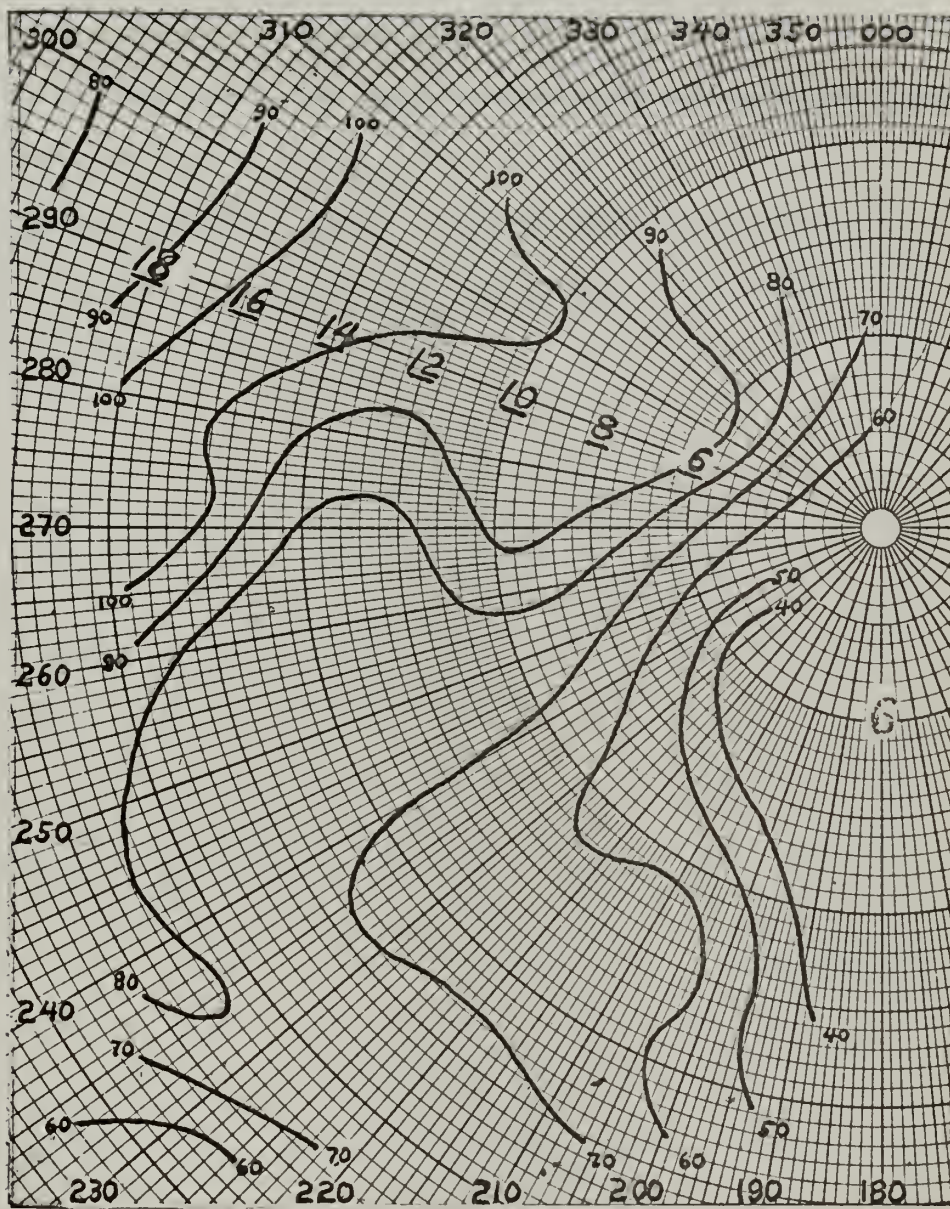
#### AND MOSS BEACH

In these curves, wave direction ( $\psi_0$ ) in degrees from true north is plotted on the radials and wave period (T) in seconds is plotted on the concentric circles. In order to obtain the value of the refraction coefficient (K) the number on each isoline must be multiplied by  $10^2$ .



Graph of refraction coefficient K, off Monterey Harbor,  
18 fathoms.





Graph of refraction coefficient  $K$ , off Moss Beach,  
6 fathoms.



## APPENDIX IV

### TABULATED WAVE DATA

This appendix is a tabulation of the hindcasted values of  $H_0$  and  $T$ , and the computed values of breaker height and wave run-up on the beach. Locations of the two points for which computations are made are listed below and shown in Fig. 1:

Monterey Harbor	36-37.15N, 121-52.65W
Moss Beach	36-37.23N, 121-56.82W

				Monterey Harbor				Mass Beach						
Date	Time	$\psi_0$	T	$H_0$	k	$H_0'$	$H_0'/T^2$	$H_0$	R	k	$H_0'$	$H_0'/T^2$	$H_0$	R
08	1000	250	8.2	9.1	.20	1.8	.027	3.7	2.3	.71	6.5	.097	9.5	4.9
08	1600	250	8.2	10.5	.22	2.3	.034	4.5	2.6	.71	7.5	.112	10.5	5.1
08	2000	280	16.8	18.6	.29	5.4	.019	12.2	8.6	.98	18.2	.064	30.0	16.3
08	2030	280	16.3	25.4	.30	7.6	.029	15.6	9.5	1.00	25.4	.095	37.7	19.1
08	2200	280	15.0	37.0	.35	13.0	.058	22.0	12.7	.95	35.0	.155	45.5	20.0
09	0400	290	16.5	35.0	.42	14.8	.054	25.8	14.9	.97	34.0	.124	46.2	22.1
09	1200	290	15.2	28.0	.45	12.6	.055	21.8	12.6	1.05	29.4	.133	39.7	17.3
09	1600	290	15.2	28.0	.45	12.6	.055	21.8	12.6	1.05	29.4	.133	39.7	17.3
10	0730	300	14.3	15.0	.56	8.4	.041	15.8	9.7	1.05	15.7	.077	23.7	12.9
10	1830	290	13.8	10.6	.49	5.2	.027	10.7	6.8	1.01	10.7	.056	18.3	10.7
11	0000	290	13.4	9.1	.49	4.5	.025	9.5	5.9	1.00	9.1	.035	17.1	10.2

February 1960

## Monterey Harbor

## Moss Beach

Date	Time	$\psi_0$	T	$H_0$	k	$H_0'$	$H_0'/T^2$	$H_B$	R	k	$H_0'$	$H_0'/T^2$	$H_B$	R
26	1030	310	15.0	10.1	.71	7.2	.032	14.4	9.0	1.00	10.1	.045	18.3	10.1
26	1500	310	14.8	11.5	.70	8.1	.037	15.4	9.2	1.00	11.5	.031	22.8	14.0
26	1630	270	15.4	34.0	.34	11.6	.049	20.6	11.9	1.00	34.0	.143	44.2	20.1
26	2230	270	13.7	20.0	.42	8.4	.045	15.1	8.6	.76	15.2	.081	23.6	12.3
27	0800	270	14.4	13.6	.36	4.9	.024	10.6	6.9	.80	10.9	.052	19.0	11.2
27	1730	270	14.4	9.9	.36	3.6	.017	8.3	6.3	.80	7.9	.038	15.0	8.7
28	0230	270	14.0	7.4	.39	2.9	.015	6.8	5.1	.80	5.9	.030	13.0	7.0

October 1950

## Monterey Harbor

## Moss Beach

Date	Time	$\psi_0$	T	$H_0$	k	$H_0'$	$H_0'/T^2$	$H_3$	R	k	$H_0'$	$H_0'/T^2$	$H_3$	R
12	0500	250	12.8	5.3	.21	1.1	.007	2.9	2.8	.75	4.0	.024	8.4	5.8
12	0800	265	15.2	12.8	.33	4.2	.018	9.6	6.9	.85	10.9	.047	19.5	11.6
12	1030	270	15.4	20.0	.39	7.8	.033	15.2	9.2	1.00	20.0	.084	30.6	16.0
12	1430	270	15.4	20.0	.39	7.8	.033	15.2	9.2	1.00	20.0	.084	30.6	16.0
12	1630	270	16.0	14.3	.33	4.7	.017	10.8	7.8	1.01	14.4	.056	24.6	14.4
13	0000	270	15.4	10.2	.39	4.0	.016	9.3	6.8	1.00	10.2	.043	18.5	10.9
13	0600	270	13.7	6.0	.48	2.9	.015	6.8	5.7	.77	4.6	.024	9.7	6.7

February 1926





## Monterey Harbor

## Moss Beach

Date	Time	$\Psi_0$	T	$H_0$	k	$H_0'$	$H_0'/T^2$	$H_B$	R	k	$H_0'$	$H_0'/T^2$	$H_B$	R
29	0400	315	12.9	9.2	.86	7.9	.047	15.1	8.2	1.00	9.2	.055	15.7	9.3
29	1600	315	12.9	26.0	.86	22.4	.134	30.2	14.6	1.00	26.0	.156	33.6	13.5
30	0400	320	11.2	14.0	.95	13.3	.106	18.9	9.4	.92	12.9	.103	18.5	8.8
30	1500	320	11.8	10.1	.96	9.7	.070	15.6	8.7	.93	9.4	.068	15.2	8.0
01	0100	320	12.4	8.7	.95	8.3	.054	14.3	8.4	.95	8.3	.054	14.3	8.4
01	1130	320	12.5	5.6	.95	5.3	.034	10.3	6.0	.95	5.3	.034	10.3	6.0

April 1915

## APPENDIX V

## SURFACE WIND OBSERVATIONS AT MONTEREY AIRPORT

Direction, steady speed, and gusts of surface wind are given below.

Speeds are expressed in knots.

February 1960

<u>Time (PST)</u>	<u>8 Feb</u>	<u>9 Feb</u>
0100	S 9	WSW 13, 19
0200	S 11	WSW 13
0300	S 11	W 20, 26
0400	SSW 15, 21	W 18, 20
0500	S 10	W 24
0600	S 15, 23	W 10
0700	S 15, 24	W 13, 22
0800	SSE 18, 24	WSW 12
0900	S 23	W 12
1000	SSW 25, 33	W 14
1100	SWS 19	W 8
1200	SW 12	W 13
1300	SSW 14	W 15, 24
1400	SW 17	W 19
1500	SW 19	W 14
1600	WSW 15	W 10
1700	SW 14	SW 5
1800	SW 14	SW 8
1900	WSW 14	SSW 8
2000	SW 15	SSW 9
2100	WSW 14, 22	SW 10

2200	WSW 16, 23	S 10
2300	WSW 16	SE 6
2400	WSW 17, 23	SW 13

2



February 1953

No observations from 2225 to 0425.

<u>Time (PST)</u>	<u>22 Feb</u>	<u>23 Feb</u>
0525		NNW 22, 30
0625		N 24, 30
0725	Less than 10 knots	NNW 21
0825		NNW 19
0925		NNW 19
1025		NNW 17
1125		N 15
1225	NNW 10	NNW 14
1325	NW 12	NW 12
1425	WNW 10	NNW 15
1525	W 11	N 15
1625	W 15	N 14
1725	WNW 10	NW 10
1825	WNW 8	NNW 9
1925	WNW 10	NNW 5
2025	W 14	NNW 6
2125	W 15, 21	NNW 6

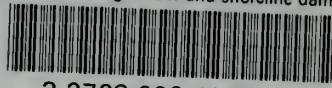
October 1950

No observations from 2225 to 0425.

<u>Time (PST)</u>	<u>26 Oct</u>	<u>27 Oct</u>
0525	Calm	SSE 3
0625	Calm	SSE 2
0725	Calm	SSE 2
0825	NE 1	SSE 4
0925	SE 6	SSE 1
1025	E 17, 29	SSW 4
1125	E 18, 29	SW 5
1225	SE 22, 38	SW 12
1325	SE 24, 40	SW 12
1425	SSE 25, 43	SW 12
1525	S 20, 34	SW 4
1625	SSE 28, 42	SW 6
1725	SW 16	Calm
1825	S 14	Calm
1920	S 14	Calm
2025	SSW 16	SE 2
2125	SSW 18	Calm

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Storms causing harbor and shoreline dama



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